SOUND AND HUMAN IMPACTS ON BELUGA WHALES IN COOK INLET, ALASKA

By

Rachael E. Blevins

Recommended:

Dr. Peter Dahl

Dr. Marc Lammers

Dr. Maribeth Murray

Dr. Terrance Quinn, II

Dr. Shannon Atkinson
Advisory Committee Chair

Dr. Franz Mueter
Chair, Graduate Program in Fisheries Division

Approved:

Dr. Joan Braddock,
Interim Dean, School of Fisheries and Ocean Sciences

Dr. John Eichelberger
Dean of the Graduate School

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Date

SOUND AND HUMAN IMPACTS ON BELUGA WHALES IN COOK INLET, ALASKA

A

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Rachael E. Blevins, B.S.

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Abstract

Cook Inlet beluga whales (CIBs) are a geographically and genetically isolated population residing in Cook Inlet, Alaska year round. The population declined by approximately 50% between 1994 and 1998 and was listed as endangered under the Endangered Species Act in 2008. The original decline was attributed to overharvest; however, the population has failed to rebound despite the virtual absence of harvest since 1998. This suggests that other factors, such as declining prey availability, increased predation, contaminants, disease, climate change, catastrophic events, habitat loss, unauthorized take, and underwater noise pollution, may be limiting the population's recovery. The goal of this dissertation research was to study the potential impacts of underwater noise on the CIB population. The objective of Chapter 1 was to study CIB acoustic behavior to gain a greater understanding of how CIBs utilize sound. The objective of Chapter 2 was to measure underwater sound levels in Cook Inlet to understand the background noise levels with which CIBs must cope. The objective of Chapter 3 was to document reactions of CIBs to noise disturbance utilizing local ecological knowledge to allow insight into the potential impacts of noise on beluga behavior. The results of Chapter 1 showed that belugas exhibit significant seasonal and spatial variation in calling behavior which suggested differences in habitat usage or differences in the surrounding environment, including background noise levels. The results of Chapter 2 showed that root mean square sound pressure levels exhibited high variation with the highest levels recorded in the 100 Hz frequency band. The seasonal differences in sound levels observed in this study were likely due to greater small vessel traffic and oil and gas development activities in the summer than the winter. In Chapter 3, participants reported observations of CIBs exhibiting avoidance reactions to noise sources including boats, planes, explosions, pile driving, construction, and cars. The results of this

chapter showed that noise is perceived to alter beluga behavior and possibly beluga distribution in Cook Inlet. This dissertation research showed that underwater noise has the potential to affect CIBs, however the cost of this impact remains unclear and warrants further study. In light of the lack of support for many of the proposed factors limiting the population and the need for further research for many of these factors, it would be valuable to consider the cumulative effects of these multiple stressors. While their potential impact may be small individually, when combined, these factors may have a synergistic and significant impact on individual whales and, in turn, on the CIB population. Management of cumulative effects may be necessary to ensure the recovery of this endangered population.

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Introduction

Beluga whales, *Delphinapterus leucas*, are medium-sized odontocetes adapted to life in Arctic and subarctic waters. They belong to the family Monodontidae along with the narwhal, *Monodon monoceros*. Based on the theory that belugas add one growth layer to their teeth per year (Hohn and Lockyer 1999, NMFS 2008), they have an estimated lifespan of over 60 years (NMFS 2008). Adults measure 4 – 5.5 m in length and weigh up to 1600 kg. Calves are born grey and gradually transition to their distinctive white color between 5 – 12 years of age (Jefferson *et al.* 1993). Belugas lack a true dorsal fin having a dorsal ridge instead. They are unique among cetaceans in that their cervical vertebrae are not fused allowing them to turn their head. Both characteristics are thought to be adaptations to living in ice-covered habitats along with their thick blubber layer (NMFS 2008). Belugas are also unique in that they molt, rubbing against sand or gravel in the summer to remove their top layer of skin. Other physical characteristics of beluga whales are their bulbous, flexible melon and their thick layer of blubber which gives them a bulky body shape. Beluga whales are capable of producing a wide array of vocalizations. They possess one of the largest vocal repertoires of any cetacean species (Jefferson *et al.* 1993). This talent earned them the nickname "sea canaries," so named by Arctic whalers in the 1800s who heard the belugas through the hulls of ships (Sjare 1991).

Beluga whales are gregarious, traveling in pods ranging from a few individuals to hundreds of whales (Jefferson *et al.* 1993). Pod structure is not fixed, but pods are generally composed of either adult males or a mixture of females, calves, and immature whales. They inhabit a discontinuous circumpolar distribution in the Northern Hemisphere. Belugas are found in the open ocean, on the continental shelf, and in coastal, estuarine, and riverine waters in the United States, Canada, Russia, and Greenland (Jefferson *et al.* 1993). Most beluga populations

undergo extensive migrations between their wintering and summering areas with the exception of the St. Lawrence Estuary and Cook Inlet stocks. In Alaska there are five management stocks: Bristol Bay, eastern Bering Sea, eastern Chuckchi Sea, Beaufort Sea, and Cook Inlet, the smallest stock (O'Corry-Crowe *et al.* 2003).

The Cook Inlet beluga population is a genetically and geographically isolated population (O'Corry-Crowe *et al.* 2003) that remains in Cook Inlet year-round (Hobbs *et al.* 2005). Cook Inlet is a semi-enclosed tidal estuary in south central Alaska approximately 370 km long and 48 km wide. It is fairly shallow, not exceeding 73 m deep in most places (NMFS 2015). Several major rivers flow into the inlet at the northern end depositing a large amount of glacial silt. The southern end of the inlet is connected to Shelikof Strait and the Gulf of Alaska. Cook Inlet is dominated by strong tidal regimes with an average range of 9 m per day. The location and geometry of the inlet, the water inputs, and the tides create gradations in turbidity, salinity, and temperature (Blackwell and Greene 2002).

The Cook Inlet beluga population was estimated to be 1293 in 1979 (NMFS 2008), and this estimate was the basis of the population's carrying capacity of 1300 utilized by the National Marine Fisheries Service. Between 1994 and 1998, the population of Cook Inlet beluga whales shrunk by approximately 50% from 653 to 347 (Hobbs *et al.* 2000). This decline was attributed to overharvest by subsistence hunters (Mahoney and Shelden 2000). The second lowest population estimate came in 2011 when the population was estimated to be 284. The most recent stock assessment in 2014 estimated the population to be 340 individuals. In addition to the decline in the population, the Cook Inlet beluga population may have undergone a composition change. In 1995, experienced hunters reported a high abundance of belugas and a larger portion of grey colored young than in previous years which suggests that reproductive rates are high

(CIMMC 1996). In 2000, hunters observed that there were few white belugas remaining in Cook Inlet suggesting a change in the population structure of the stock with a higher abundance of young or gray whales (Huntington 2000).

Comparing the beluga distribution in the 1990s with the distribution in the 1970s, the habitat of Cook Inlet belugas has contracted (Rugh *et al.* 2000). The reason for this contraction is not known but several hypotheses have been proposed including: predator avoidance as killer whales' ability to travel into the upper inlet is limited by shallow water depth (Shelden *et al.* 2003); reduction in prey availability (Moore *et al.* 2000); or habitat preference (Goetz *et al.* 2007). The historical range of Cook Inlet belugas likely extended into the Gulf of Alaska (Laidre *et al.* 2000), but since the population decline they have rarely been seen south or east of West Forelands (Hobbs *et al.* 2005) despite historically being regular visitors in lower Cook Inlet, especially in the spring and fall (Rugh *et al.* 2000). The northward contraction in their range has confined the beluga habitat to the areas of Cook Inlet with the highest human population density (Rugh *et al.* 2010) putting them at increased risk of human impacts. Hunters have also observed a change in the distribution of belugas in recent years that may date back to long-term changes beginning in the 1950s. Belugas could be found in great numbers in Trading Bay in June and July until 20-25 years ago (Huntington 2000). Prior to the 1990s, belugas were regularly seen in the lower inlet (Speckman and Piatt 2000). In past decades, belugas were found in Kachemak Bay in early spring and in the fall, and large pods of belugas were seen seasonally in Halibut Cove (Stanek 1994). Sightings in lower Cook Inlet have decreased dramatically and group sizes have become smaller compared to the 1970s and 1980s (Speckman and Piatt 2000). Since 2000 there have been almost no sightings of belugas below Kenai River. These changes in beluga distribution have co-occurred with an observed decrease in abundance (Huntington 2000).

Alaska Natives attribute these changes in distribution largely to changes in the fish runs that attract belugas to certain areas of the upper inlet (Huntington 2000).

The small-scale, daily movements of beluga whales in Cook Inlet are governed by the tides (Huntington 2000). The large-scale, seasonal distribution patterns exhibited by beluga are attributed to the distribution of fish (CIMMC 1996, Huntington 2000, Hobbs *et al.* 2005). Belugas are most commonly seen in the upper inlet, typically arriving in late April (Huntington 2000). The Cook Inlet beluga population exhibits high site fidelity during the summer, preferring shallow, coastal areas near river mouths in upper Cook Inlet (Moore and DeMaster 2000). During the summer, belugas often move from the open waters of the inlet into the mouths of major rivers including the Kenai, Crescent, Susitna, Beluga, Little Susitna, Theodore, Lewis, and Crescent rivers. They also are found in Knik Arm, Chickaloon Bay, the Forelands (Stanek 1994), and Turnagain Arm (Huntington 2000). Belugas remain in the upper inlet into November despite ice formation (Huntington 2000). Belugas' winter habitat is largely undefined. Belugas are rarely seen during the winter months, but when they are sighted it is in the central inlet in more dispersed numbers compared to the summer months (Moore and DeMaster 2000).

The decline of the Cook Inlet beluga population was largely attributed to overharvest by subsistence hunters (Mahoney and Shelden 2000). The Cook Inlet beluga population's site fidelity and isolation makes them vulnerable to overharvest. Alaska Natives have been hunting beluga whales in Cook Inlet for hundreds of years (de Laguna 1975). In archeological studies of prehistoric native communities of Alutiiq Eskimos and Dena'ina Athabascans in Kachemak Bay and near West Foreland, de Laguna (1975) found bones that were most likely beluga. Historically, hunting techniques took advantage of belugas' behavior of traveling upriver during high tide. One technique was to use a spearing tree, a tree driven upside down into the river

bottom from which hunters would spear belugas as they swam by (Mahoney and Shelden 2000). Another technique involved the use of movable fences. After belugas swam upriver during high tide, the fence would be placed in the mouth of the river to trap the whales as they returned downstream during the ebb tide (Fall 1981). In the 1900s, beluga whaling in Cook Inlet changed drastically. First, the demographics of beluga hunters changed as many people moved to the growing metropolis of Anchorage. The group of beluga hunters expanded to include the native Dena'ina of Cook Inlet, Alaska Natives that had moved into the Anchorage area, and Alaska Natives that participated in hunts while visiting the Cook Inlet area (Mahoney and Shelden 2000). The resident hunters were from Anchorage, Matanuska-Susitna, Kenai, and Tyonek. Hunters that visit the area come from Kotzebue Sound, Norton Sound, the Seward Peninsula, the Yukon-Kuskokwim Delta, Bristol Bay, and Barrow (Stanek 1994). It was suggested that Alaska Natives from other areas may have come to hunt in Cook Inlet due to conditions in the inlet being better than in other areas and the whales being more desirable (Stanek 1996). Hunters have reported that the belugas in Cook Inlet have a larger body size than other populations of belugas (Huntington 2000). This is attributed to a better food source (Huntington 2000). Modern hunting of beluga whales is conducted from motor boats in shallow waters (Mahoney and Shelden 2000). Beyond subsistence harvest, in the early 1900s the population was subject to large, intermittent commercial harvest. The Beluga Whaling Company conducted commercial harvests of Cook Inlet belugas in Beluga River, taking 151 belugas between 1917 and 1920 (Bower and Aller 1917, 1918; Bower 1919, 1920, 1921). Anecdotal evidence suggests there may have also been commercial harvests of approximately 100 belugas in the Beluga River during the 1930s (Klinkhart 1966, Fall *et al.* 1984, Lowry 1985, Stanek 1994). The Cook Inlet beluga population was also the target of a sport fishery in the 1960s. The Beluga Whale Hunt

Club operated in the Kenai area from 1963 – 1965. However, the club was not particularly successful and harvest by the group was minimal (Mahoney and Shelden 2000).

Harvest numbers for the Cook Inlet beluga population are not well known due to the lack of reporting and the difficulty in quantifying the number of belugas taken by non-resident Alaska Natives. Between the 1930s and the 1940s, it is estimated that the native Dena'ina in Tyonek harvested 6-7 belugas per year (Fall *et al.* 1984). After the 1940s, hunters in Cook Inlet shifted their effort to moose which were becoming more abundant, and subsistence beluga hunting essentially stopped (Stanek 1996). In the 1970s beluga hunting was taken up again by Alaska Natives in Cook Inlet (Mahoney and Shelden 2000). Three belugas were taken in 1979 (Stanek 1996), and at least one beluga was taken each year from 1981-1983 by the Tyonek Dena'ina (Fall *et al.* 1984). Between 1987 and 1993, beluga takes ranged from 16-24 belugas a year (Stanek 1994). From 1994 to 1998 21 – 147 belugas were taken each year with an average of 72 belugas reported harvested annually, but the number of belugas taken was most likely higher due to harvest by non-residents and belugas that were struck and lost (Mahoney and Shelden 2000). A harvest of 72 belugas per year from the Cook Inlet beluga population is approximately five times the calculated potential biological removal, the maximum number of animals that may be removed from the population while allowing it to maintain its optimum sustainable population (Hill and DeMaster 1998). This increase in beluga harvest is likely due to the increase in the number of hunters with the expansion of the hunter demographics as hunters from other areas moved to the Anchorage area or traveled to the Anchorage area to hunt. Alaska Natives voluntarily suspended beluga hunting in Cook Inlet in 1999 due to concern over the dwindling population (Moore and Demaster 2000). Unfortunately, in the decade following the end of subsistence hunting for Cook Inlet belugas, there have been no signs of recovery in the

population (Hobbs *et al.* 2008). Therefore, there must be other factors limiting their recovery. Other drivers have been proposed including declining prey availability, increased predation, contaminants, disease, climate change, catastrophic events, habitat loss, unauthorized take, and underwater noise pollution (NMFS 2015).

It has been proposed that changes in prey abundance or availability may be responsible for the failure of the Cook Inlet beluga population to recover (NMFS 2015). Belugas are opportunistic feeders, foraging on fish and a variety of invertebrates including octopus, squid, crab, shrimp, clams, mussels, and worms. Cook Inlet belugas feed on runs of whitefish, *Coregonus nelsonii,* in the spring (Huntington 2000) and remain in the upper inlet to feed on subsequent fish runs. After the whitefish runs, belugas feed on returning adult eulachon, or hooligan, *Thaleichthys pacificus*, then king salmon, *Oncorhynchus tshawytscha*, sockeye salmon, *O. nerka*, pink salmon, *O. gorbuscha*, chum salmon, *O. keta*, and coho salmon, *O. kisutch* (Huntington 2000). They will also eat lingcod, *Ophiodon elongates*, tomcod, *Microgadus tomcod*, starry flounder, *Platichthys stellatus*, steelhead trout, *Oncorhynchus mykiss*, northern pike, *Esox lucius*, and Arctic grayling, *Thymallus arcticus* (Huntington 2000). Alaska Natives have observed changes in the timing of fish runs and an overall decrease in fish abundance that they believe is affecting belugas (Huntington 2000). The composition of fish species in the Gulf of Alaska changed significantly between 1980 and 2000 (Anderson and Piatt 1999) which may have had an impact on the prey abundance or quality for predators such as beluga whales. Sport harvests in eulachon, a significant food source for belugas, in upper Cook Inlet have declined since 1980, which could indicate declines in their populations (Stratton and Cyr 1997, Howe *et al.* 1999), but there are insufficient data on the species to confirm decreasing eulachon populations. There are no studies that provide evidence that Cook Inlet belugas are

undernourished, suggesting that lack of prey availability is not the only factor limiting recovery of the population.

Another theory is that increased predation on belugas by killer whales, *Orcinus orca*, is limiting recovery of the population (NMFS 2015). Historically beluga predation by killer whales was low due to spatial separation of the two species with orcas spending more time in the lower inlet and belugas being concentrated in the upper inlet (Murray 1979). Before 1990, orcas were only observed in the upper inlet twice. However, since that time sightings have become more frequent with some reports of orcas traveling into the upper inlet at least once a year (Shelden *et al.* 2003). It has been suggested that the decline in Steller sea lion, *Eumetopias jubatus*, and harbor seal, *Phoca vitulina*, populations in Alaska has caused orcas to switch their prey base, and that orcas have been increasing their trips into the upper inlet to hunt belugas in the absence of other prey sources (Shelden *et al.* 2003). Since 1985 there have been 14 documented encounters between killer whales and belugas in Cook Inlet. Of these interactions, 11 resulted in beluga injury or mortality (Shelden *et al.* 2003). When interactions occurred in Turnagain Arm, belugas were chased, stranded, or eaten, or their carcasses were found later. Eight documented beluga deaths were attributed to killer whales in Turnagain Arm between 1991 and 2000 (Shelden *et al.* 2003). The current level of beluga mortality due to killer whale predation, an average of one per year, is minimal (Shelden *et al.* 2003). However, it is possible that this mortality is an underestimate due to the sinking of carcasses, consumption of the entire beluga, or level of decomposition preventing identification of cause of death (Shelden *et al.* 2003). Strandings elicited by orca presence may be a greater threat than direct mortality due to predation. However, Cook Inlet beluga whales often survive live stranding through a tide cycle until they can refloat on the next high tide (Vos and Shelden 2005). Only 12 belugas perished out of 650

that live-stranded between 1988 and 2000 (Moore *et al.* 2000). Given the low mortality due to predation by killer whales and the low mortality due to stranding, it seems unlikely killer whale predation is the main factor limiting recovery of the Cook Inlet beluga population.

Contaminants and disease have also been proposed as limiting factors in the recovery of the Cook Inlet beluga population (NMFS 2015). However, studies have shown Cook Inlet belugas have the lowest concentrations of PCBs and chlorinated pesticides of the North American beluga stocks (Becker *et al.* 2000). They also have the lowest loads of the heavy metals mercury, selenium, and cadmium of North American beluga stocks (Becker *et al.* 2000). The effects of contaminants on Cook Inlet beluga health is likely lower than that of any other North American beluga stock (Becker *et al.* 2000). Some Alaska Native hunters have reported an increase in the frequency of lesions, tumors, and irregularities in the skin and blubber (CIMMC 1996). Contrary to these observations, in necropsies no tumors, lesions, or abnormalities have been found, and parasite loads did not exceed the normal range (Burek 1999a, 1999b). The relatively low contaminant load and low incidence of abnormalities in necropsies do not lend support to the theory that contaminants or disease are preventing recovery of the population.

Direct effects of climate change on the Cook Inlet beluga population are difficult to study. Potential indirect effects of climate change are easier to identify. Climate change has the potential to reduce or degrade beluga habitat or the habitat on which their prey rely (NMFS 2015). The warming water temperatures associated with climate change have the potential to exacerbate threats to the population, which may be low at present. Warmer water temperatures may increase the frequency of disease outbreaks in the future (NMFS 2015). Warming water temperatures could also lead to an increase in beluga predation; the abundance of sharks,

potential beluga predators, may increase in Cook Inlet or new shark species may expand their distribution into the inlet (O'Brien *et al.* 2013). Warmer water temperatures in combination with changes in pH and salinity could affect the toxicity and bioavailability of contaminants (Schiedek *et al.* 2007), which could increase their impact on Cook Inlet belugas.

Underwater noise pollution has also been proposed as a potential limiting factor (NMFS 2015). Sound is transmitted much more efficiently underwater than light, and marine mammals have evolved to utilize sound. Marine mammals use sound to communicate, forage, avoid predators, and navigate using echolocation (Richardson *et al.* 1995). Due to marine mammals' reliance on sound, ambient noise is an important characteristic of the marine environment. Ambient noise is generated by both natural and anthropogenic sources. Humans have been a source of noise in the marine environment since the transition from wind-driven to mechanized shipping (NRC 2005). Anthropogenic noise sources include commercial shipping, oil and gas activities, boating, military activity, research, and construction. Ocean noise can be divided into low frequency (10-500 Hz), mid frequency (500 Hz-25 kHz), and high frequency (over 25 kHz) bands (Hildebrand 2009). Noise generated by human activity dominates the low frequency band of marine ambient noise. The most significant sources of low frequency ambient noise are commercial shipping and seismic exploration (Hildebrand 2009). Low frequency sounds have very low attenuation in the marine environment resulting in dispersal across entire ocean basins (Au and Hastings 2008). In the mid-frequency band, sonar and small vessels generate noise on a regional scale (Hildebrand 2009). Some sonar emits sound at high frequency; however, such high frequency sounds often have low dispersal due to rapid attenuation limiting its effect to local scales.

Anthropogenic noise can affect marine mammals through masking or behavioral disturbance. Masking occurs when anthropogenic noise frequencies overlap with the frequency of signals significant to marine mammals, preventing detection of the signal. Masking can interfere with communication, hunting, or echolocation. Disturbance occurs when noise elicits a reaction or a change in behavior. Disturbance has the potential to interrupt critical activities such as feeding or mating. There has been a paucity of directed studies to evaluate the effects of noise on Cook Inlet belugas. Beluga hunters in Cook Inlet have observed belugas react to human activity (Huntington 2000). Prior to the suspension of the subsistence harvest, belugas had grown wary of hunters (Huntington 2000). Some Alaska Native hunters report that belugas avoid motorboats and may be able to recognize individual boats (Stanek 1996). Studies of other populations have shown that belugas react to noise from boats, aircraft, construction, explosions, and oil and gas activities (Richardson *et al.* 1995). Climate change may cause underwater noise to increase in coming years due to decreased sound absorption from ocean acidification (Hester *et al.* 2008). As sound absorption decreases, anthropogenic sound can travel further increasing the number of animals potentially affected or increasing the number or sound sources that may be audible to an individual animal at a given time.

In light of the failure of the Cook Inlet beluga population to recover in the virtual absence of subsistence harvest, it is important to determine other factors limiting recovery. The Cook Inlet beluga population's small size and its separation from other stocks may decrease its resilience to further natural or anthropogenic disturbance (Vos and Shelden 2005), increasing the chance of extinction. The lack of support for other limiting factors, including decreases in prey availability, increases in predation, contaminants, and disease indicates that further investigation into other potential limiting factors such as underwater noise is warranted. The goal of this

dissertation research was to study the potential impacts of underwater noise on the Cook Inlet beluga population. The objective of Chapter 1 was to study Cook Inlet beluga acoustic behavior and to determine if calling behavior varied temporally or spatially within the inlet. This study provided a greater understanding of how Cook Inlet belugas utilize sound. In Chapter 2, I sought to measure sound levels in Cook Inlet to understand the background noise levels with which Cook Inlet belugas must cope. Correlations between the differences in beluga acoustic behavior in Chapter 1 and the differences in ambient underwater noise levels in Chapter 2 provided insight into potential effects of underwater noise on beluga acoustic behavior. The objective of Chapter 3 was to document reactions of Cook Inlet belugas to noise disturbance. This final chapter allowed insight into the potential impacts of noise on facets of beluga behavior other than acoustic behavior, providing a more complete picture on the potential effects of noise on the Cook Inlet beluga population.

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Chapter 1 : Spatial and temporal patterns in the acoustic behavior of beluga whales, *Delphinapterus leucas*, in Cook Inlet, Alaska[1]

Abstract

Cook Inlet beluga whales (CIB) are an endangered population residing in Cook Inlet, Alaska year-round. We characterized the calling behavior of CIB to gain a greater understanding of the phonations utilized by this population. Bottom-moored hydrophones were deployed at Eagle Bay in summer 2009 and at Trading Bay in summer and winter 2009 sampling at 25 kHz with a 10% duty cycle. Phonations were qualitatively analyzed and categorized as a whistle, pulsed call, or click train. Four thousand ninety-seven calls were analyzed and 91 unique call contours were identified, 27 of which were observed in all three hydrophone deployments. Cook Inlet beluga whistles were quantitatively analyzed using a custom Matlab program. A chi-square test showed the call category usage at Eagle Bay during summer 2009 and those at Trading Bay during summer 2009 and winter 2009-2010 differed significantly ($p < 0.001$). Pulsed calls were more common during the summer months than the winter months, and click trains within the frequency band (up to 12.5 kHz) were more common in Eagle Bay than Trading Bay. The variation in calling behavior suggests differences in habitat usage or differences in the surrounding environment, including background noise.

[1] Blevins, R., S. Atkinson, and M. Lammers. Spatial and temporal patterns in the calling behavior of beluga whales, *Delphinapterus leucas*, in Cook Inlet, Alaska. Submitted to *Marine Mammal Science*

Introduction

In Alaska, there are five management stocks of beluga whales, *Delphinapterus leucas*: Bristol Bay, the eastern Bering Sea, the eastern Chuckchi Sea, the Beaufort Sea, and Cook Inlet, the smallest stock (O'Corry-Crowe *et al.* 2003). The Cook Inlet beluga population (referred to as CIB) is a genetically and geographically isolated population (O'Corry-Crowe *et al.* 2003) that remains in Cook Inlet year-round (Figure 1.1) (Hobbs *et al.* 2005). Cook Inlet is a semi-enclosed tidal estuary in south-central Alaska (Figure 1.1). It is approximately 370 km long and 32 km wide and is fairly shallow, not exceeding 60 m deep in most places. Several major rivers flow into the inlet at the northern end depositing a large amount of glacial silt. Cook Inlet is dominated by strong tidal regimes with a typical range of 9 meters per day, the largest in the United States (Mulherin *et al.* 2001). The Cook Inlet watershed is home to 400000 residents, approximately 2/3 of Alaska's population, and includes the city of Anchorage (Cook Inlet Keeper 2015, see www.inletkeeper.org/about/watershed).

Between 1994 and 1998 the CIB was estimated to decline by almost fifty percent (Hobbs *et al.* 2000). This decline was attributed to overharvest by Alaska Natives and led to the voluntary suspension of the subsistence hunt in 1999 (Moore and DeMaster 2000). Coincident with the population decline, the CIB habitat range began to shrink (Rugh *et al.* 2000). The historical range of CIB covered most of Cook Inlet and likely included occasional forays into the Gulf of Alaska (Laidre *et al.* 2000), but since the population decline, they have rarely been observed south or east of West Forelands, located mid-inlet (Figure 1.1) (Hobbs *et al.* 2005). This northward contraction in their range coincides with the areas of Cook Inlet that have the highest human population densities including Anchorage, the largest city and port in Alaska (Rugh *et al.* 2010). This puts them at increased risks from the potential impacts of human

interactions. Since the regulation of the subsistence harvest, the CIB has shown no sign of recovery (Hobbs *et al.* 2008). In the last decade, the population has shown an average decline of 1.1% per year (Allen and Angliss 2010). Due to this continued decline, the CIB was listed as endangered under the Endangered Species Act (ESA) in 2008 (73 FR 62919), and critical habitat was designated in 2011 (76 FR 20180). The failure of the population to rebound in the virtual absence of subsistence harvest suggests there are additional factors limiting the population's recovery. Many factors have been proposed including declining prey availability, increased predation, contaminants, disease, climate change, catastrophic events, habitat loss, unauthorized take, and underwater noise pollution (NMFS 2015), but there are currently few data to support any of these factors.

Underwater noise pollution is a growing concern for many marine mammal populations. Sources of anthropogenic noise in the marine environment include commercial shipping, oil and gas activities, boating, military activity, research utilizing active hydroacoustics, and construction. Human-generated noise in the marine environment has the potential to mask signals that are important to marine mammals such as calls from conspecifics, echolocation signals, predator calls, and the sounds of their prey (Richardson *et al.* 1995) which may limit population growth and hinder the recovery of an endangered population (Tyack 2009) such as the CIB. The problem of underwater noise is likely to increase in coming years due to increased human activity in the marine environment. Increasing water temperatures and ocean acidification affiliated with climate change may further raise underwater noise levels in some areas (Sehgal *et al.* 2010). With the anticipated increase in the level of ambient noise and the declining beluga population in Cook Inlet, it is important to understand how environmental noise

may affect these animals. First a greater understanding is needed of how these animals use sound including the sounds they produce.

Beluga whales are capable of producing a wide array of phonations, and they possess one of the largest acoustic repertoires of any cetacean species (Jefferson *et al.* 1993). This characteristic earned them the nickname "sea canaries," so named by Arctic whalers in the 1800s who heard beluga calls through the hulls of their ships (Sjare 1991). The acoustic repertoire of beluga whales has been studied in Cunningham Inlet in the Canadian High Arctic (Sjare and Smith 1986b), the White Sea in Russia (Bel'kovich and Shekotov 1993; Belikov and Bel'kovich 2005, 2007, 2008), Bristol Bay, Alaska (Angiel 1997), the St. Lawrence Estuary, Canada (Faucher 1988), Svalbard, Norway (Karlsen *et al.* 2002), and the Churchill River, Manitoba (Chmelnitsky and Ferguson 2012). Beluga repertoires vary between populations (Karlsen *et al.* 2002), but have not been reported to exhibit inter-annual variation (Sjare and Smith 1986a). Beluga phonations have been grouped into three categories: whistles, pulsed calls, and clicks (Sjare 1991). Whistles and pulsed calls are both social calls. Whistles are narrow band tonal phonations that range in frequency from 260 Hz to 20 kHz with peak frequencies between 2 and 5.9 kHz (Sjare and Smith 1986a, 1986b). Pulsed calls are bursts of broad band pulses with a high repetition rate (Vergara *et al.* 2010). They range in frequency from 400 Hz to 12 kHz with peak frequencies from 1 to 8 kHz. Clicks are broadband short-duration repetitive signal trains used for echolocation (Vergara *et al.* 2010) with peak frequencies between 40 and 60 kHz and 100 and 120 kHz (Au *et al.* 1985, 1987; Au 1993). Beluga phonations are known to vary based on behavior, school size, and school structure (Karlsen *et al.* 2002), but the specific function of many of their calls remains largely unknown (Sjare 1991).

The study described here made opportunistic use of data collected as part of a larger acoustic monitoring project in Cook Inlet (see Lammers *et al.* 2013). The objective of this study was to characterize CIB calling behavior and to determine whether it varied between two locations and between seasons. Expected differences in habitat usage, group composition, and ambient noise environment led us to hypothesize that beluga calling behavior varies spatially within Cook Inlet and seasonally. Variation could indicate differences in habitat importance or different levels of human impact due to anthropogenic noise.

Methods

Site selection

This study is an opportunistic use of data collected by the Cook Inlet Beluga Acoustic (CIBA) project, an acoustic monitoring program to document habitat usage by the CIB. Two out of eight sites from the CIBA project, Eagle Bay and Trading Bay (Figure 1.1), were chosen for this study.

Eagle Bay was selected as the upper inlet location and lies within the CIB Critical Habitat Area 1 (76 FR 20180). It is located in Knik Arm approximately 14 km north of Anchorage (Figure 1.1), a city within the Cook Inlet watershed with a population of almost 300000 people. In order for Cook Inlet belugas to reach Eagle Bay from other locations in the inlet, they must travel through the major shipping lanes of the Port of Anchorage. Eagle Bay is also adjacent to the military base Joint Base Elmendorf-Richardson with aircraft that generate aerial noise detectable underwater (Lammers *et al.* 2013). The water is shallow and visibility is limited due to the high load of glacial silt carried into the bay from Eagle River. Eagle River, which terminates at Eagle Bay, serves as salmon spawning habitat for all five Pacific salmon species during the summer season (ACE 2013), which is the likely reason belugas occupy the area.

Trading Bay is a wide bay located immediately north of the West Foreland and fed by the McArthur River (Figure 1.1). It was selected to represent the mid inlet and the southern end of the documented Cook Inlet beluga range as beluga whales are rarely seen south of West Foreland (Hobbs *et al.* 2005). Trading Bay is located within the CIB Critical Habitat Area 2 (76 FR 20180) and may serve as important winter habitat for the CIB (Lammers *et al.* 2013). Trading Bay is a more remote area compared to the upper inlet being further from human population centers, but there are several oil rigs in the area and more vessels transit through this region of the inlet than Eagle Bay.

Data collection

Ecological Acoustic Recorders (EARs), bottom-moored autonomous recorders described in Lammers *et al.* (2008), were configured as specified in Lammers *et al.* (2013) and deployed in Eagle Bay during summer 2009 for 47 days and in Trading Bay during summer 2009 for 94 days and winter 2009-2010 for 83 days (Table 1.1, Figure 1.1) as part of the CIB study described in Lammers *et al.* (2013). They were designed specifically to withstand deployment conditions present in Cook Inlet (Lammers *et al.* 2013). The EARs were programmed to record on a 10% duty cycle, recording 30 seconds of every 5 minutes. This duty cycle was expected to be ample to detect the signals of phonating belugas milling or traveling through the EARs' listening range over a minimum period of 10-20 minutes.

The detection range of the EARs was not tested at Eagle Bay or Trading Bay, but an informal test of the EARs' listening range in Cook Inlet was previously conducted (Lammers *et al.* 2013). The test utilized an artificial 15 – 20 kHz frequency modulated sweep projected at a source level of 140 dB re 1 μPa. The EAR was suspended at 3 m depth below a stationary vessel. The projector was suspended at 2 – 4 m depth below a moving vessel, and the sweep was

projected at several distances from the EAR. The maximum detection range varied from 2.2 to 3.3 km (Lammers *et al.* 2013). The EARs were set to sample at 25 kHz. Low frequency roll off occurred around 17 Hz, and the anti-aliasing filter was set to 80% of the sampling frequency providing an effective bandwidth of approximately 10 kHz. This bandwidth was expected to be sufficient to record most beluga social calls and lower frequency components of echolocation clicks. At the end of the deployment period, the EARs were retrieved, and the data were downloaded.

Data analysis

A custom Matlab™ algorithm was used to calculate the percentage of time tonal signals were present in each file (MATLAB Release 2011b, The MathWorks, Inc.). The files, 30 second recordings, were then ranked by decreasing percentage of tonality and the top ten percent were visually inspected for beluga calls using CoolEdit 96, a music editing software (Syntrillium Software Corporation). When a recording with beluga phonations was identified, the surrounding files both before and after the recording were checked until five consecutive files lacked any beluga calls, suggesting that belugas had likely traveled outside the detection radius of the hydrophone or ceased phonating.

After the files containing beluga phonations were identified, they were grouped into summer and winter months. Summer was defined as July 1 – September 30 and winter was defined as December 1 – February 28. The Eagle Bay hydrophone had a shorter summer deployment (Table 1.1) recording from July 7 – August 16 for the summer months.

For the qualitative analysis, CoolEdit 96 was used to identify individual beluga calls. Calls with a signal to noise ratio sufficient to make them visible on the spectrogram and aurally distinguishable for the researcher were described and categorized as a whistle, a narrow-band

non-echolocating call with a tonal quality; a pulsed call, a broadband non-echolocating call lacking tonal quality; or a click train (Figure 1.2). Calls that were too faint to be categorized were excluded from analysis. The relative abundance of each call category was calculated for each data set by dividing the number of calls in each call category by the total number of calls in the dataset. Calls were then grouped into encounters. For this study, an encounter was defined as a period of beluga acoustic activity separated from other phonations by more than 60 minutes (Lammers *et al.* 2013). This time period was selected based on the tendency of belugas to move with the predominant tidal flow, the strong tidal currents present in Cook Inlet, and the detection range of the EARs (Lammers *et al.* 2013). The duration (in minutes) of each encounter and its separation (in hours) from the previous encounter were determined. A Kruskal-Wallis test, a nonparametric analysis of variance, was used to compare the encounter durations and separations between datasets. For each encounter the number of whistles, pulsed calls, and click trains were calculated. Mean encounters were calculated for each data set by taking the mean of the number of calls within each call category, and the relative abundance of each call category was determined. A chi-square test was used to compare the number of whistles, pulsed calls, and click trains in Eagle Bay during summer (EBS), Trading Bay during summer (TBS), and Trading Bay during winter (TBW). EBS was compared to TBS to evaluate spatial variation. TBS was compared to TBW to evaluate seasonal variation.

Once calls were categorized, the whistles and the pulsed calls were assigned a contour, the shape created by plotting the frequency of the call over time. This measure preserved as much detail as possible but avoided grouping calls into broad contours. Contours were determined based on visual and aural characteristics observed in the qualitative analysis. The primary characteristics used to distinguish contours were the beginning and ending frequency

slope direction (up or down). The overall frequency trend (ascending, descending, or neutral) and the number of inflections were used further to discriminate contours. Finally, the difference between the minimum and maximum frequency of the call, determined visually, and the approximate duration of the call were used to reach the final contours. Throughout contour classification, each call was checked against the previously identified contours. If it could not be classified as one of the already observed contours, it was assigned to a new contour. Once all beluga calls had been qualitatively analyzed, the contours were reviewed and contours with similar characteristics were combined. Contours that were only observed once were not included in the total contour count for the study.

Once the qualitative analysis was complete, each individual beluga whistle was manually extracted from the files. Another custom Matlab™ program was used to quantitatively measure the whistles. Whistles that overlapped other calls could not be analyzed in the program and some other whistles had an insufficient signal to noise ratio to be accurately measured by the program. The custom program returned 68 variables describing the frequency, duration, and shape of the whistle including the beginning frequency, ending frequency, maximum frequency, minimum frequency, frequency range (the difference between the minimum and maximum frequency), and duration.

A classification tree analysis (Breiman *et al.* 1984) was conducted in R (R Core Team 2015) to assign whistles to contours using the beginning slope (positive, negative, or zero), the ending slope (positive, negative, or zero), the number of inflections, the beginning frequency, the ending frequency, the minimum frequency, the maximum frequency, the frequency range, and the call duration measured in the quantitative analysis as predictors. A reduced regression tree analysis was conducted using only the beginning slope (positive, negative, or zero), the ending

slope (positive, negative, or zero), the number of inflections, the frequency range, and the call duration measured in the quantitative analysis. Duration was excluded for a further reduced analysis. Calls were separated into groups based on their beginning and ending slope (Up-Up, Up-Down, Up-Flat, etc.) and a regression tree analysis was run on these groups individually using the number of inflections, the beginning frequency, the ending frequency, the minimum frequency, the maximum frequency, the frequency range, and the call duration measured in the quantitative analysis.

Results

Thirty-nine beluga encounters containing 4097 calls were qualitatively analyzed, 3079 calls in 24 encounters from Eagle Bay summer 2009 (EBS), 214 calls in 8 encounters from Trading Bay summer 2009 (TBS), and 804 calls in 7 encounters from Trading Bay winter 2009 (TBW) (Figure 1.3). Of these, 547 whistles were quantitatively analyzed, 336 from EBS, 83 from TBS, and 128 from TBW.

The length of encounters did not vary between locations or seasons. However, the time between encounters varied significantly ($p < 0.001$) between the data sets (Figure 1.4). Mean encounter duration (with standard error) was 107 minutes (SE 22.06) in EBS, 19 minutes (SE 3.94) in TBS, and 60 minutes (SE 26.11) in TBW. The mean encounter separation (with standard error) was 26 hours (SE 19.70), 72 hours (SE 19.05), and 120.3 hours (SE 59.59) for EBS, TBS, and TBW, respectively.

The relative abundance of whistles, pulsed calls, and click trains differed significantly ($p < 0.001$) between the three datasets (Table 1.3). Whistles were the most abundant call category in all three data sets (Table 1.2) with the highest relative abundance occurring in TBW (90.6% of the mean encounter, Table 1.2). Pulsed calls had a higher relative abundance in the summer

(38.6% for EBS and 30.5% for TBS) than in the winter (5.9% for TBW, Table 1.2). Pulsed calls were almost as common as whistles (46.5% of calls) in the mean EBS encounter (Table 1.2). While the relative abundance of pulsed calls in the mean TBS data set was similar to EBS, the relative abundance of whistles (68.1%) greatly exceeded that of pulsed calls (Table 1.2). Click trains were the rarest call category, making up a larger proportion of the calls in Eagle Bay (14.9% of calls in the mean encounter) than in Trading Bay (1.4% and 3.5% for summer and winter respectively, Table 1.2). The TBS data was compared to the TBW data to examine for seasonal variation. The call category usage between summer and winter differed significantly ($p < 0.001$) with a higher abundance of pulsed calls in the summer than the winter (Table 1.3). A greater abundance of whistles in the winter made up the difference. The TBS data set was compared to the EBS data set to evaluate spatial variation. Call category usage between the two locations differed significantly ($p < 0.001$) with a higher abundance of click trains in Eagle Bay than Trading Bay (Table 1.3).

Eleven hundred eighty-three calls were assigned to 91 unique call contours based on their visual and aural characteristics as described in the methods section; twenty-seven of these call contours were present in all three datasets (Figure 1.5, Table 1.4). Thirty-five were present in EBS and TBW, but not TBS. Eight were present in TBS and EBS but not TBW, and 2 were present in both Trading Bay datasets but not Eagle Bay. There were 13, 2, and 2 contours unique to the EBS, TBS, and TBW datasets, respectively (Figure 1.5). Whistles were distributed approximately equally among frequency trends, determined by the relationship between the beginning and ending frequency of the whistle. The most common frequency trend was descending, having a lower ending frequency than beginning frequency, with 436 calls. Three hundred ninety-four calls had an ascending trend where the ending frequency was higher than the

beginning frequency. Three hundred fifty-three calls had a neutral trend where the beginning and ending frequencies were approximately equal. Whistle contours fit into one of eight groups based on beginning and ending slope of the frequency contour: Up-Up, Up-Down, Up-Flat, Down-Up, Down-Down, Down-Flat, Flat-Down, and Flat-Flat (Table 1.4). The Up-Down group was the most abundant containing 319 calls in 18 contours. The second most abundant group was the Down-Down group containing 207 calls in 13 contours. The Up-Up group was comprised of 183 calls in 14 contours. The Down-Up group contained 181 calls in 10 contours. The Down-Flat and Flat-Flat groups contained 83 calls each in 4 and 2 contours respectively. The Flat-Down group was made up of 73 calls in 4 contours. The least abundant group was the Up-Flat group with 54 calls in 3 contours. Whistle complexity was determined based on the number of inflections, points where the slope of the contour changed direction, in the call (Table 1.4). Simple whistles were defined as those with 0 or 1 inflection. Moderately complex whistles had 2 or 3 inflections. Whistles with 4 to 6 inflections were classified as high complexity whistles; those with 7 or more inflections were classified as very high complexity whistles. The abundance of whistles decreased with increasing complexity. Simple whistles were most common with 916 calls. Two hundred six calls had moderate complexity. There were 43 and 18 calls with high and very high complexity, respectively. Twenty-five pulsed call contours were identified in the qualitative analysis based on their aural characteristics and the appearance of their spectrogram. However, pulse repetition rate was not calculated as part of this study; therefore, these contours were not analyzed further.

A majority of whistles were emitted below 8 kHz with a high concentration of whistles emitted between 1 and 2.5 kHz. Very few whistles were emitted above 9 kHz. A small number of whistles began or ended above the 12.5 kHz maximum detected by the EARs. These whistles

were excluded from analysis as the entire whistle was not captured. Whistle duration ranged from 0.108 s to 2.811 s with a mean of 0.40 s (SE 0.01). More information on the characteristics of the 27 whistle contours observed across all three datasets is available in Table 1.4. For information on all the whistle contours observed in the present study, see the Appendix. Pulsed calls were not quantitatively analyzed. Further description of the pulsed contours will not be presented in this text.

The classification tree analyses resulted in poor classification of beluga calls. For the analysis that utilized beginning slope, the ending slope, the number of inflections, the beginning frequency, the ending frequency, the minimum frequency, the maximum frequency, the frequency range, and the call duration for classification, the best tree was a five-node tree that had a prediction error of 84.3% indicating that if the tree was used to classify a new call there would be an 84.3% chance the call would be misclassified into the wrong contour. For the reduced analysis that used the beginning slope, the ending slope, the number of inflections, the frequency range, and the call duration the best tree was once again a five node tree. This tree had an 83.7% prediction error. The analysis utilizing only the beginning slope, the ending slope, the number of inflections, and the frequency range resulted in a 4 node tree with an 87.0% prediction error. Pruning did not improve the performance for these three trees. When calls were separated based on their beginning and ending slopes only five groups contained enough calls for analysis, Up-Up, Up-Down, Up-Flat, Down-Up, Down-Down. The best performance was for the Down-Down group. The best tree within the group had three nodes with a 73.0% prediction error. The lowest prediction errors for the other four groups ranged from 78.2% to 84.2%.

Discussion

Cook Inlet beluga calling behavior exhibited seasonal and spatial variation. We detected more whistles than either pulsed calls or clicks within our recording bandwidth across all seasons and locations. Whistles were also the most common beluga call category recorded in Cunningham Inlet, Canada (Sjare and Smith 1986b), Svalbard, Norway (Karlsen *et al.* 2002), Bristol Bay, Alaska (Angiel 1997), the White Sea, Russia (Belikov and Bel'kovich 2007), and Churchill River, Manitoba (Chmelnitsky and Ferguson 2012). Pulsed calls made up a larger proportion of the repertoire in the summer compared to the winter (Table 1.2), suggesting that pulsed calls may be more heavily utilized by belugas during the summer months in Cook Inlet. Interpretation of this result is limited, however, by the fact that we recorded only seven beluga encounters over the winter season. Further studies of the winter repertoire of CIB should be conducted to determine if this trend holds true in other locations in Cook Inlet.

Increased rates of certain types of pulsed calls have been associated with social interaction in belugas in Cunningham Inlet, Canada (Sjare and Smith 1986a). A similar relationship between types of pulsed calls and social interaction have been observed in other cetacean species including Southern right whales (*Eubalaena australis*) (Clark 1982), bottlenose dolphins (*Tursiops truncatus*) (Gish 1979), and spinner dolphins (*Stenella longirostris*) (Brownlee 1983). CIB tend to aggregate in dense groups during the summer months (Rugh *et al.* 2000) so the apparent increase in usage of pulsed calls during this time could be due to higher levels of social interaction as CIB travel in these larger groups. Another possibility is the greater abundance of pulsed calls in summer may be due to increased foraging activity leading to increased emission of terminal buzzes (Verfuss *et al.* 2009). These buzzes have very short interclick intervals which could have led to misclassification as a pulsed call if this interval was short enough to be

indistinguishable. Increased usage of pulsed calls during the summer months may also be indicative of the presence of young calves. Captive-born beluga calves have produced pulsed calls exclusively through the first weeks of life (Vergara and Barrett-Lennard 2008, Manuel Castellote, personal communication[2]) and produced more pulsed calls than any other call category during the first seven months of life (Vergara and Barrett-Lennard 2008). Based on traditional ecological knowledge (TEK) of Alaska Native beluga hunters, CIB calve from April to August (Huntington 2000) and calf surveys are conducted in Cook Inlet in August based on the expectation that calves will be 2 months of age or younger at this time (Hobbs *et al.* 2012). During our defined summer season (July-September) CIB calves should be only a few months old suggesting they will be emitting mostly pulsed calls. While the greater use of pulsed calls in the summer may be due to the presence of young calves, we cannot confirm their use of these habitats with our data. A potential mother-calf contact call has been identified for captive belugas (Vergara and Barrett-Lennard 2008) and for wild belugas in the St. Lawrence Estuary (Vergara *et al.* 2010) and the Churchill River, Manitoba (Chmelnitsky and Ferguson 2012). Unfortunately, the tonal component of the call lies above the bandwidth of the EARs and could not be detected in this study. Future acoustic monitoring for the presence of this call category would indicate the presence of mother-calf pairs.

The spatial variation in call usage also offered some interesting insights. Click trains made up a greater proportion of the repertoire in Eagle Bay than Trading Bay (Table 1.2) within our frequency band. The higher abundance of click trains in Eagle Bay may be indicative of differences in environment. Compared to Trading Bay, Eagle Bay is shallower and has a higher sediment load in the water column, limiting visibility. These conditions may lead to increased

[2] Manuel Castellote, National Marine Mammal Laboratory, Alaska Fisheries Science Center/NOAA, 7600 Sand Point Way NE, Seattle, WA 98115-6349. September 2014.

echolocation for navigation. The variation in click train usage could also be due to differences in beluga behavior in these two locations. Belugas have been observed hunting at Eagle Bay during the summer so the increased use of click trains could be due to foraging activity (Verfuss *et al.* 2009). The low abundance of click trains in the other data sets (Table 1.2) does not mean belugas are not echolocating in Trading Bay. The sampling frequency used in this study (25 kHz) limited detection of click trains. In a study of captive belugas, Au *et al.* (1985) found that a majority of acoustic energy of beluga echolocation signals lies between 20 and 60 kHz, above the 12.5 kHz maximum frequency detected by the EARs. It is likely that many CIB click trains were emitted at frequencies above the range of the EARs.

Despite having the shortest deployment time (Table 1.1), the Eagle Bay summer EAR recorded almost four times the number of CIB calls as the Trading Bay winter EAR and almost fifteen times the number of CIB calls as the Trading Bay summer EAR. The greater number of calls in Eagle Bay could indicate that more individuals or larger groups were utilizing this habitat (Figure 1.1), but that could not be confirmed using our single hydrophone mooring configuration. However, the longer encounter duration and shorter encounter separation at Eagle Bay supports the idea that CIB have a more intensive usage of this habitat, spending more time in Eagle Bay than in Trading Bay. This agrees with previous movement studies of CIB. Prey availability is suspected to be one of the strongest drivers of CIB distribution (Moore *et al.* 2000). Belugas are known to aggregate in dense groups in the northern reaches of the inlet near river mouths during the summer (Rugh *et al.* 2000) likely pursuing migrating eulachon (*Thaleichthys pacificus*) and Pacific salmon (*Oncorhynchus* sp.). The area around Eagle River has been a documented concentration region for CIB during August (Hobbs *et al.* 2005), and

Eagle River supports runs of all five Pacific salmon species (ACE 2013). During the fall and winter, belugas disperse south into mid-inlet waters (Hobbs *et al.* 2005).

Ninety-one call contours were identified in the CIB repertoire based on visual and aural characteristics. The number of contours identified in this study greatly outnumbered those found in other beluga studies, but this increase in the number of identified contours compared to repertoire studies in other populations is likely due in part to differences in classification. For this study we maintained a large number of contours rather than grouping them into broad, diverse contours as had been done previously. The object of maintaining a large number of contours was to preserve a high level of detail. Many of the contours utilized by CIB fit into the broad categories defined in previous studies (Sjare and Smith 1986b, Karlsen *et al.* 2002, Chmelnitsky and Ferguson 2012). The two CIB contours in the Flat-Flat whistle group, including CI-3 (Table 1.4) could be classified as the unmodulated frequency whistles CT1 observed in St. Lawrence belugas (Faucher 1988). CI-3 could also be classified as W1 (Chmelnitsky and Ferguson 2012), NA4 or MD4 (Angiel 1997), 1a or 1b (Sjare and Smith 1986b), 4 (Belikov and Bel'kovich 2007), and 1a or 1b (Karlsen *et al.* 2002). Eight CIB whistle contours within the Up-Up group, including CI-9, CI-33, and CI-65 (Table 1.4) could be grouped into the CT2 upsweep (Faucher 1988). Faucher (1988) identified an upsweep-downsweep CT3 whistle that could include 7 CIB whistle contours including CI-1 and CI-4 (Table 1.4). These whistles also resemble W4a and W4b (Chmelnitsky and Ferguson 2012); NA2, NA7, MD15, and MD18 (Angiel 1997); 3a (Sjare and Smith 1986b); W12 (Belikov and Bel'kovich 2007); and 3a (Karlsen *et al.* 2002). Five CIB whistle contours including CI-6 (Table 1.4) could be classified as CT4 downsweep whistles (Faucher 1988). Three Down-Up CIB contours, including CI-2 and CI-10 (Table 1.4) could be classified as CT5 downsweep-upsweep whistles (Faucher 1988), W5b

(Chmelnitsky and Ferguson 2012), NA15 or MD48 (Angiel 1997), 7 (Sjare and Smith 1986b), W2 (Belikov and Bel'kovich 2007), or 5a (Karlsen *et al.* 2002). Previous researchers often refrained from discriminating contours with two or more inflections, rather lumping them into one group such as CT6 in St. Lawrence (Table 1.4). Twenty-five whistle contours with 3 or more inflections, including CI-24, CI-26, and CI-47 (Table 1.4) were identified in Cook Inlet. For a full discussion of how Cook Inlet beluga contours fit into Sjare and Smith's (1986b) classification system which has also been used in the St. Lawrence Estuary (Faucher 1988) and Svalbard, Norway (Karlsen *et al.* 2002), see the Appendix. Some contours identified in Cook Inlet were not explicitly described in previous studies, but it is difficult to know if they are unique due to the large groupings identified in other populations. It is not known whether the differences used to distinguish CIB contours are biologically significant to belugas.

Decreasing whistles, whistles with a greater beginning frequency than ending frequency, were most common in Cook Inlet as was observed in a study of captive belugas (Fish and Mowbray 1962). As has been described in other beluga populations (Sjare and Smith 1986b, Angiel 1997, Karlsen *et al.* 2002, Belikov and Bel'kovich 2007, Chmelnitsky and Ferguson 2012), flattened whistles were common in Cook Inlet. Of the 547 quantitatively analyzed calls, 101 had 1 inflection or less with a difference of less than 50 Hz between the ending and beginning frequency.

While there were some CIB contours common in all three datasets, each dataset contained unique contours and some contours were seen in only two of the three datasets (Figure 1.5). The differences in contour usage between locations and between seasons may indicate that the different habitats are used for different activities or by different groups with different compositions. Individual- or group-specific calls have not been confirmed in belugas but have

been documented in other toothed whale species including killer whales (Ford 1989), bottlenose dolphins, Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) (Caldwell and Caldwell 1965), and sperm whales (*Physeter macrocephalus*) (Rendell and Whitehead 2003). Vergara *et al.* (2010) have proposed that female belugas and their offspring may develop variants of a potential contact call that function in long-term recognition. In narwhals (*Monodon monoceros*), the beluga's closest extant relative, calls are more similar within a herd than between herds, suggesting that narwhals may have individual- or group-specific calls (Marcoux *et al.* 2011). The greater number of shared contours between Eagle Bay in the summer and Trading Bay in the winter than Trading Bay in the summer and winter may be due to movement of individuals from Eagle Bay in the summer to Trading Bay in the winter. The variation in number of unique calls could also be due to differences in sample size. As the number of calls in EBS greatly exceed that of the other two datasets it is likely that more contours would be observed in EBS compared to TBS and TBW.

It appears that CIB may produce mixed calls, phonations comprised of both tonal and pulsed components. With our single hydrophone mooring configuration, it was not possible to locate calling belugas. However, the identical start and stop times of the tonal and pulsed components of some phonations strongly suggest that both components were produced simultaneously by a single individual. These calls were uncommon and could not be confirmed as true mixed calls and were therefore not included in the analysis. Mixed calls have been identified in wild belugas in Svalbard, Norway (Karlsen *et al.* 2002) and Churchill River, Manitoba (Chmelnitsky and Ferguson 2012) and in captive belugas (Vergara and Barrett-Lennard 2008). The mixed call has been documented in other odontocetes including killer whales (Schevill and Watkins 1966, Ford 1989, Filatova *et al.* 2009), bottlenose dolphins (Killebrew *et al.* 2001), false killer whales

(*Pseudorca crassidens*) (Murray *et al.* 1998), and spotted dolphins (*Stenella frontalis*) (Herzing 2000).

The poor performance of the classification tree analysis indicated that contour types could not be distinguished based on their frequency characteristics, duration, or number of inflections. This result supports the idea that beluga calls exist on a graded continuum where contour types shift into one another without discrete boundaries making it difficult to divide calls into distinct contours. This concept has been proposed in previous studies of beluga acoustic repertoires (Sjare and Smith 1986b, Faucher 1988, Karlsen *et al.* 2002, Belikov and Bel'kovich 2007, Chmelnitsky and Ferguson 2012). It has also been observed in long-finned pilot whales (*Globicephala melas*) (Taruski 1979) and false killer whales (Murray *et al.* 1998). Graded signal systems are also utilized by some primates (Rowell 1962, Rowell and Hinde 1962, Bertrand 1969, Marler 1970, Gautier 1974, Chevalier-Skolnikoff 1974, Green 1975, Schott 1975, Struhsaker 1975, Marler 1976, Fischer *et al.* 2001, Trillmich *et al.* 2004) and bird species (Miller 1979, Guilette *et al.* 2010). While graded signal systems have been recognized in many species, very few studies have attempted a quantitative analysis of graded signals (Keenan *et al.* 2013). If we wish to define signal systems as graded or discrete, a quantitative definition needs to be developed. Or, if we accept that signal systems are likely not strictly graded or strictly discrete, as has been observed in many primate species (Hammerschmidt and Fischer 1998), a metric for measuring the level of gradedness or discreteness of the system is needed. Despite the graded nature of beluga calls, there is value to contour classification. While it is not known which call characteristics are biologically significant to belugas, bottlenose dolphins appear to distinguish different calls based on contour not frequency parameters (Ralston and Herman 1995, Harley 2008). Caution must be used attempting to classify calls based solely on acoustic characteristics

as belugas are capable of altering frequency and duration of their calls in response to noise (Lesage *et al.* 1999). We relied more heavily on shape characteristics than frequency characteristics to distinguish contours due in part to this ability of belugas to alter the frequency of their calls.

This opportunistic study utilizing passive acoustic data provides a starting point for future studies of beluga phonations in Cook Inlet. Seasonal and spatial differences in calling behavior among CIB and calls commonly used by CIB were identified. This information could be helpful for future repertoire studies or for auto-detection of beluga calls. As the methodology used to collect these data was designed to evaluate beluga movements rather than the characterization of beluga calls, limitations of the data prevent broader conclusions based on the data.

Future acoustic studies in Cook Inlet with a wider frequency band would improve our understanding of CIB's use of click trains and could also allow the detection of the mother-calf contact call identified in other beluga populations (Vergara and Barrett-Lennard 2008, Vergara *et al.* 2010, Chmelnitsky and Ferguson 2012). Utilizing a 10% duty cycle we likely missed a large proportion of the beluga calls and cannot say we observed all contours used by CIB. To characterize the entire repertoire of CIB a higher duty cycle would be needed. Also we had no behavioral observations to provide context for the recorded calls. Coordinated visual and acoustic studies could provide insight into the behavioral context of CIB phonations. Unfortunately, beluga acoustic encounters were limited in the winter months. More data on winter acoustic behavior will be needed to characterize the winter repertoire of CIB.

This study did not attempt to evaluate the effects of environmental conditions on beluga calling behavior. Cook Inlet experiences very large tides leading to considerable tidal currents that can have a large impact on ambient noise conditions. Tidal phase has been shown to effect

use of call categories in the St. Lawrence Estuary (Faucher 1988). The effect of environmental conditions on CIB acoustic activity warrants further investigation. This study was also not designed to evaluate changes in beluga calling behavior in response to changes in background noise. The issue of underwater noise is a rising concern, and the effects of underwater noise on CIB should be evaluated. With the proposed development projects in Cook Inlet and the potential increase in ambient noise level due to ocean acidification, it is important to understand how this endangered population uses sound, and what anthropogenic factors may influence that use.

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Table 1.1 Hydrophone Information

Information for each of the three hydrophone deployments utilized in this study including hydrophone location, season of study, latitude and longitude, hydrophone depth, and deployment and retrieval dates. The study duration is the number of days within the deployment that fell within our study definitions of summer (July-September) and winter (December-February).

Location	**Eagle Bay**	**Trading Bay**	**Trading Bay**
Season	Summer	Summer	Winter
Latitude	61 N 16.668	60 N 53.482	60 N 53.433
Longitude	149 W 44.206	151 W 38.232	151 W 38.257
Depth	27 ft.	48 ft.	48 ft.
Deployment date	7/7/09	6/30/09	12/9/09
Retrieval date	8/16/09	11/8/09	5/2/10
Study Days	7/7 – 8/16	7/1 – 9/30	12/9 – 2/28

Table 1.2 Mean Encounters

Mean number of whistles (W), pulsed calls (PC), and click trains (CT) per encounter and the relative abundance of whistle, pulsed calls, and click trains for each dataset Eagle Bay Summer (EBS), Trading Bay Summer (TBS), and Trading Bay Winter (TBW). An encounter is defined as a period of beluga acoustic activity separated from other beluga phonations by at least 60 minutes.

	EBS	**TBS**	**TBW**
Encounters	24	8	7
W/Encounter	61	17	93
PC/Encounter	46	9	17
CT/Encounter	20	0	2
Rel. Abundance W	0.465	0.681	0.906
Rel. Abundance PC	0.386	0.305	0.059
Rel. Abundance CT	0.149	0.014	0.035

Table 1.3 Chi-Square Results

Results of the chi-square analyses comparing all three datasets, Eagle Bay Summer (EBS), Trading Bay Summer (TBS), and Trading Bay Winter (TBW), comparing the winter and summer data in Trading Bay, and comparing the Eagle Bay and Trading Bay data during the summer. The p-values showed the three data sets differed significantly from each other and showed significant seasonal and spatial differences.

	EBS vs. TBS vs. TBW	**Summer vs. Winter**	**Eagle Bay vs. Trading Bay**
X^2	347.71	300.27	327.44
Degrees of Freedom	4	2	2
Critical Value	9.49	5.99	5.99
p-value	< 0.001	< 0.001	< 0.001

Table 1.4 Common Call Contours in Cook Inlet

Characteristics and descriptive statistics of the 27 call contours observed across all three datasets. For information on all the contours, see the Appendix. As seen by the number of observations, the contour number is indicative of how common the contours were with 1 being the most common and 91 the least common. Contours designated with an asterisk (*) are pulsed call contours. For whistle contours the beginning frequency slope and ending frequency slope of the contour, the overall frequency trend (ascending – ending frequency greater than ending frequency; descending – ending frequency less than beginning frequency; neutral – ending frequency and beginning frequency approximately equal), and the number of inflections (Inf.) is presented. Mean (SD) beginning frequency, ending frequency, minimum frequency, maximum frequency, and duration are presented for those contours with a statistical sample size (statistical n) greater than 1.

Contour	# Obs.	EBS n	TBS n	TBW n	Beg. Slope	End. Slope	Freq. Trend	Inf.	Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
CI-1	119	73	8	38	Up	Down	Neutral	1	3702 (3215)	3811 (3502)	3410 (3072)	4068 (3598)	0.30 (0.17)	31
CI-2	91	47	10	34	Down	Up	Neutral	1	3964 (3371)	4098 (3478)	3839 (3334)	4263 (3548)	0.31 (0.24)	8
CI-3	81	34	6	41	Flat	Flat	Neutral	0	1416 (812)	1461 (837)	1397 (821)	1490 (833)	0.57 (0.50)	22
CI-4	79	39	2	38	Up	Down	Ascending	1	1678 (1660)	1715 (1652)	1627 (1573)	1813 (1790)	0.37 (0.39)	28
CI-5	73	31	4	38	Down	Flat	Descending	0	4169 (1942)	3854 (1939)	3645 (1943)	4497 (1910)	0.75 (0.45)	13
CI-6	67	13	1	53	Down	Down	Descending	0	3764 (3766)	3889 (3727)	3382 (3452)	4222 (3986)	0.42 (0.32)	5
CI-7	64	33	1	30	Flat	Down	Descending	0	1639 (2330)	1587 (2164)	1529 (2169)	1660 (2322)	0.22 (0.09)	14
CI-8*	57	53	1	3										
CI-9	49	28	1	20	Up	Up	Ascending	0	3598 (2291)	3849 (2311)	3571 (2241)	4002 (2454)	0.15 (0.07)	14
CI-10	42	28	1	13	Down	Up	Ascending	1	3441 (3443)	3545 (3426)	3340 (3330)	3714 (3502)	0.51 (0.39)	24
CI-11*	39	27	10	2										

Table 1.4 continued…

CI-13*	51	10	5	21			
CI-19	26	12	1	13	Down	Down	Descending
CI-21*	22	18	2	2			
CI-22	21	11	1	9	Up	Flat	Ascending
CI-23*	20	16	1	3			
CI-24	20	13	1	6	Up	Down	Ascending
CI-26	18	11	3	4	Up	Down	Ascending
CI-30*	15	7	2	6			
CI-32*	14	9	1	4			
CI-33	13	9	3	1	Up	Up	Ascending
CI-41*	9	2	6	1			
CI-47	7	3	1	3	Up	Down	Neutral
CI-56	5	1	2	2	Up	Up	Ascending
CI-63*	4	2	1	1			
CI-64	4	1	1	2	Down	Down	Descending
CI-65	4	1	2	1	Up	Up	Ascending

2	6057 (2081)	5876 (2136)	5559 (2186)	6457 (2087)	0.48 (0.41)	17
0	1465 (854)	1370 (771)	1364 (777)	1486 (853)	0.50 (0.42)	8
3	5195 (3923)	5391 (3972)	5195 (3923)	5430 (3999)	0.14 (0.05)	5
3	662 (151)	860 (335)	652 (153)	867 (330)	0.26 (0.17)	10
0	2333 (2358)	2563 (2603)	2323 (2354)	2570 (2600)	0.27 (0.19)	7
3	8691	8618	7935	9155	0.81	1
2	4045	4240	4045	4508	0.27	3
2	1502	1611	1502	2442	0.38	2
0	7874	6775	6690	7874	0.28	2

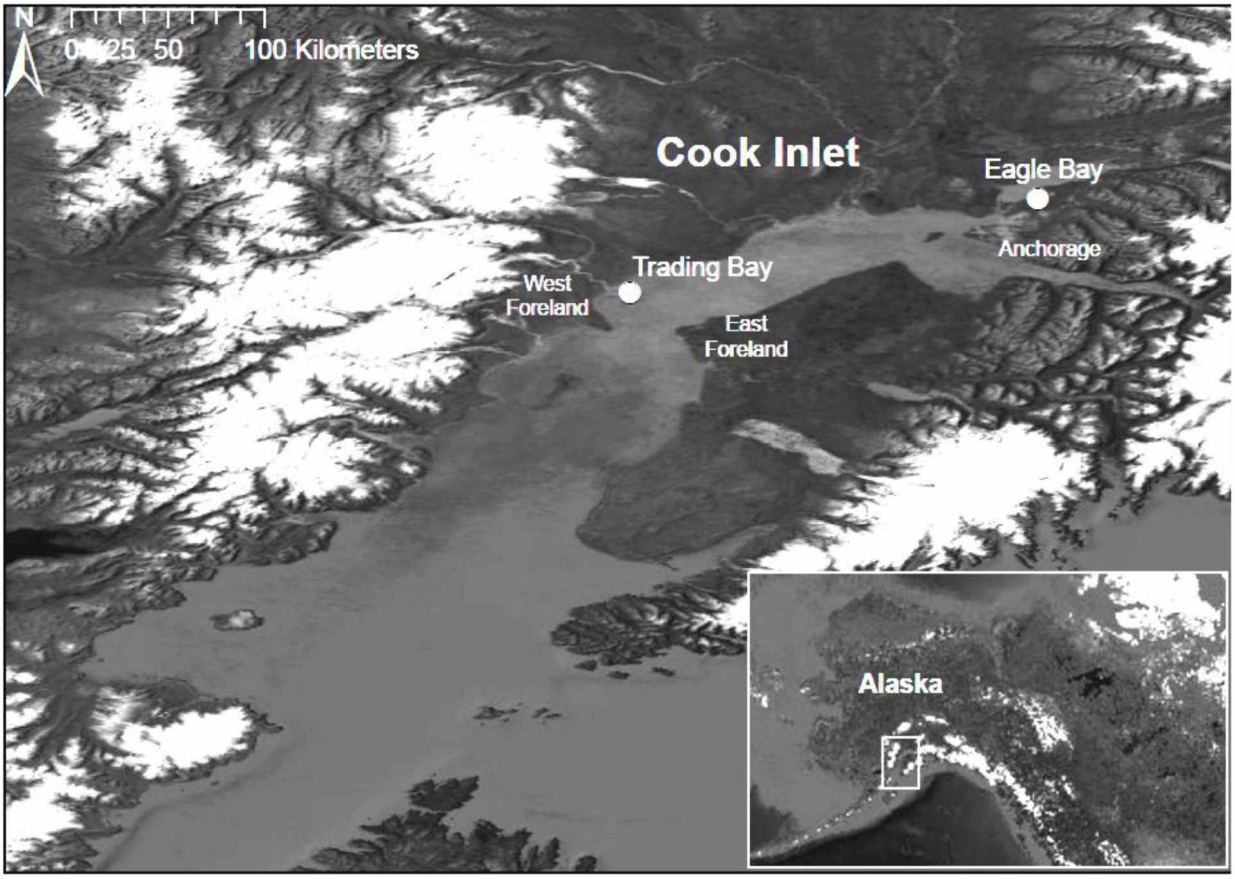

Figure 1.1 Hydrophone Mooring Locations in Cook Inlet, Alaska. Ecological Acoustic Recorder (EAR) mooring locations are indicated by the white circles. Map extent indicated by the rectangle in inset map. (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.)

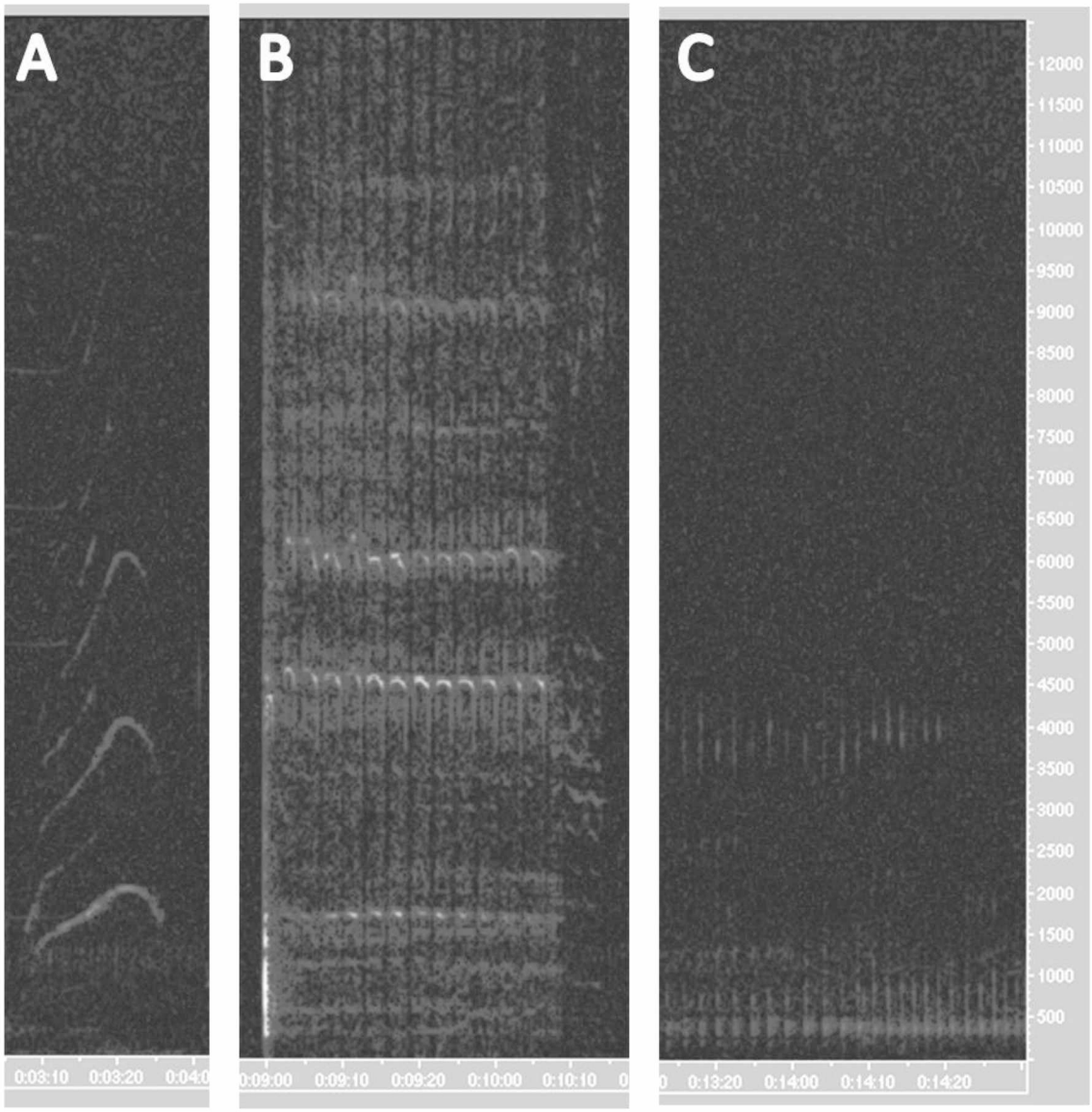

Figure 1.2 Spectrograms of Beluga Call Types. These spectrograms, visual representations of sound with frequency (Hz) on the vertical axis and time (s) on the horizontal axis, show examples of the call types used for call classification. (A) depicts a whistle, a narrow-band social call. (B) shows a pulsed call, a broad-band social call. (C) shows a click train, a series of echolocation signals.

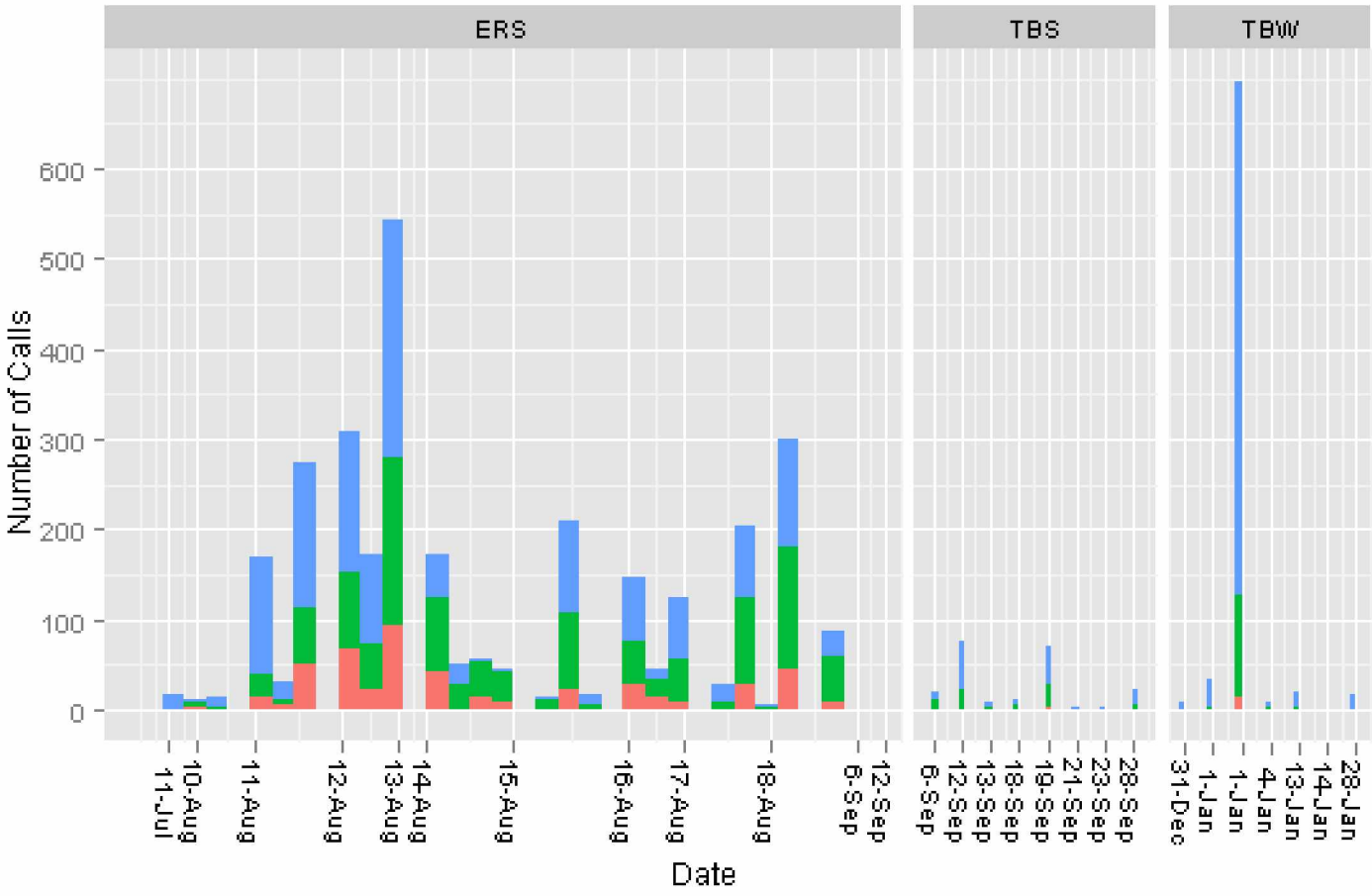

Figure 1.3 Beluga Acoustic Encounters. Number of whistles (blue), pulsed calls (green), and click trains (red) within each encounter (bars) for Eagle Bay Summer (EBS, n=24), Trading Bay Summer (TBS, n=8), and Trading Bay Winter (TBW, n=7).

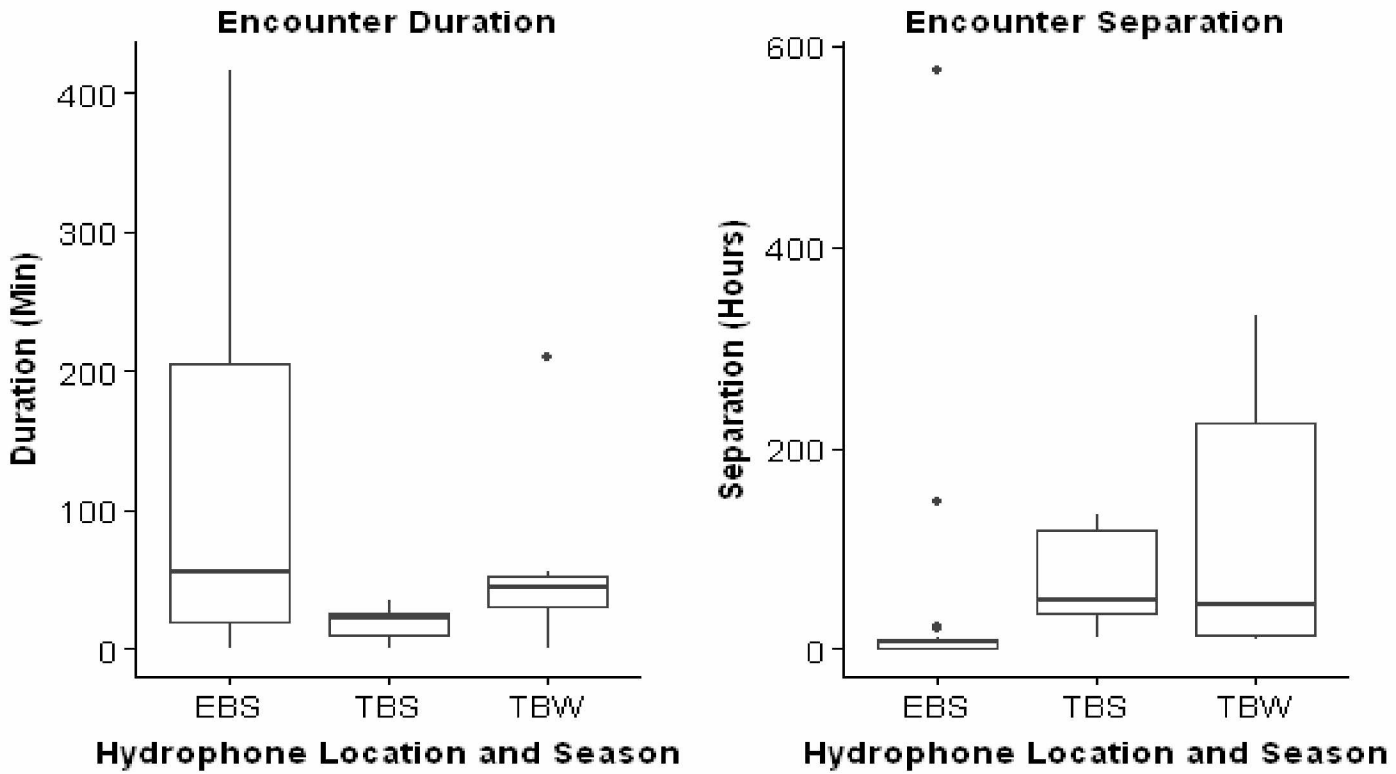

Figure 1.4 Encounter Durations and Separations. Box-and-whisker plots displaying the encounter durations and separations in minutes and time between encounters in hours for Eagle Bay Summer (EBS) (n=24), Trading Bay Summer (TBS) (n=8), and Trading Bay Winter (TBW) (n=7). An encounter was defined as a period of beluga acoustic activity separated from other acoustic activity by at least 60 minutes. The upper and lower bounds of the box represent the first and third quartiles of the data. The median is indicated by the thick line within the box, and the minimums and maximums are represented by the whiskers. The open circles represent outliers in the data, those data points with a value more than 1.5 times the inter-quartile range below or above the first and third quartiles respectively. The variance in the data highlights the irregular beluga presence in EBS, TBS, and TBW.

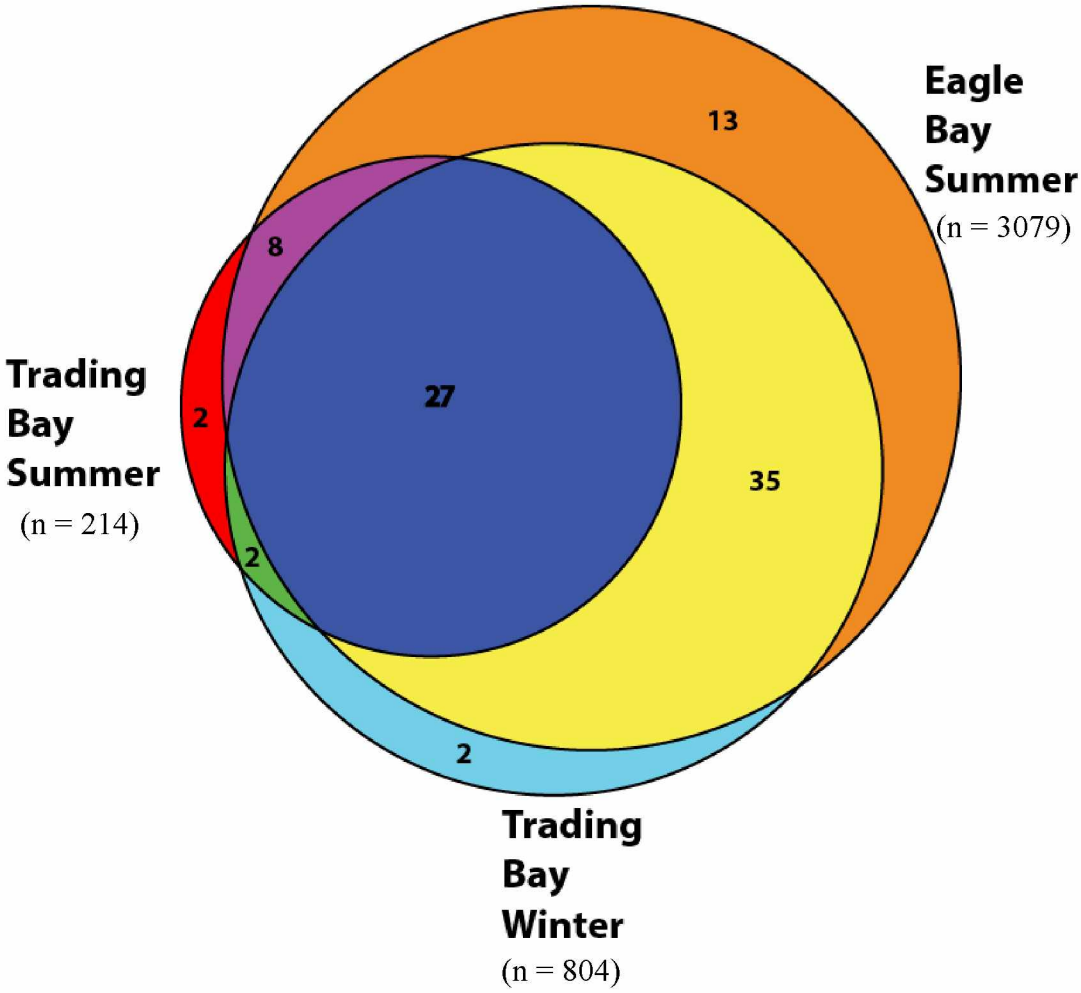

Figure 1.5 Call Contour Usage. Venn diagram comparing call contour usage between data sets. The number of shared contours between data sets is indicated in the overlapping areas. The area overlapped by all three circles represents the number of contours observed in all three data sets. Regions where only two of the circles overlap represent contours found in two of the datasets but not the third. The number of contours unique to each data set, those not seen in either of the other two datasets, is shown in the non-overlapping areas.

Appendix

Based on visual and aural characteristics, ninety-one call contours were identified in the Cook Inlet beluga repertoire, greatly outnumbering those found in other beluga studies. The greater number of contours identified in this study compared to previous repertoire studies in other populations is likely due in part to differences in classification. For this study we maintained a large number of contours rather than grouping them into broad, diverse contours as had been done previously. The object of maintaining a large number of contours was to preserve a high level of detail. Many of the contours utilized by Cook Inlet belugas fit into the broad categories defined in previous studies. As several previous studies have utilized the classification scheme outlined by Sjare and Smith (1986) (i.e. Karlsen *et al.* 2002, Faucher 1988), this appendix will aggregate the whistle contours identified in Chapter 1 (Table A.1) into the contours outlined by Sjare and Smith (1986).

Contour types 1*a* and 1*b* are unmodulated frequency, flat whistles (Sjare and Smith 1986). While contour 1*b* could not be identified in Cook Inlet due to its segmentation, contour CI-3 (Table A.1) matches contour 1*a* (Sjare and Smith 1986). In Cook Inlet, this flat whistle tended to be emitted at lower frequencies than in Cunningham Inlet where the mean frequency of this contour was 3.2 kHz (Sjare and Smith 1986), in Svalbard where the mean frequency was 4.2 kHz (Karlsen *et al.* 2002), or in the St. Lawrence Estuary where the mean frequency was 6.4 kHz (Faucher 1988). The duration of this contour was similar in Cook Inlet and Cunningham Inlet (Sjare and Smith 1986), but this contour was shorter in Svalbard where the mean duration was 0.16 s (Karlsen *et al.* 2002). Calls in this contour were longer in the St. Lawrence Estuary than the other three locations with an average duration of 0.94 s (Faucher 1988).

Contour types 2*a* and 2*b* are ascending frequency whistles lacking inflection points (Sjare and Smith 1986). In Cook Inlet, calls in the Up-Up category having 0 inflections would be grouped into category 2*a*, including CI-9, CI-28, CI-33, CI-35, CI-39, CI-40, CI-43, and CI-65 (Table A.1). In Cook Inlet, all of these calls fell below 3 kHz whereas in Cunningham Inlet calls belonging to contour 2*a* had a mean frequency of 4.7 kHz (Sjare and Smith 1986). Calls within this contour in Svalbard were similar in frequency to those in Cunningham Inlet (Karlsen *et al.* 2002), but in the St. Lawrence Estuary the mean frequency was lower at 3.8 kHz (Faucher 1988). Calls in Cook Inlet were also shorter with a mean duration of 0.25 s as opposed to 0.38 s in Svalbard (Karlsen *et al.* 2002), 0.43 s in the St. Lawrence Estuary (Faucher 1988), and 0.50 s in Cunningham Inlet (Sjare and Smith 1986). Contour 2*b* could not be identified in Cook Inlet due to its segmentation.

Contour types 3a, 3b, 3c, and 3d are ascending-descending frequency whistles. As 3a was the only unsegmented contour within this group, it was the only contour that could be identified in Cook Inlet. The Up-Down calls with 1 inflection fall into the 3a contour, including CI-1, CI-4, CI-18, CI-53, CI-57, CI-68, CI-86, and CI-87 (Table A.1). The mean minimum frequency of this contour in Cook Inlet matched the mean in Cunningham Inlet of 3.3 kHz, however the mean maximum frequency was approximately 1 kHz lower in Cook Inlet than Cunningham Inlet (Sjare and Smith 1986) and 1.9 kHz lower in Cook Inlet than Svalbard (Karlsen *et al.* 2002). The St. Lawrence Estuary had the highest mean minimum and maximum frequency for calls of this contour at 4.6 and 7.0 kHz respectively (Faucher 1988). The duration was shorter in Cook Inlet and Svalbard than in Cunningham Inlet and the St. Lawrence Estuary with mean durations of 0.28 s, 0.28s, 0.55 s, and 1.19 s respectively (Sjare and Smith 1986, Faucher 1988, Karlsen *et al.* 2002).

Contour types 4*a* and 4*b* are descending frequency whistles. Contour type 4*b* could not be identified in Cook Inlet due to its segmentation, but whistles belonging to the Up-Up category with 0 inflections, including CI-6, CI-16, CI-58, CI-72 (Table A.1) can be grouped into contour 4*a*. These calls were emitted at higher frequencies in Cook Inlet than Cunningham Inlet. The mean minimum frequency in Cook Inlet and Cunningham Inlet was 3.4 and 1.7 kHz, respectively, and the mean maximum frequency in Cook Inlet was 3.9 kHz and 3.4 kHz in Cunningham Inlet (Sjare and Smith 1986). In Svalbard, the mean minimum frequency was 5.3 kHz and the mean maximum frequency was 6.1 kHz (Karlsen *et al.* 2002). In the St. Lawrence Estuary, calls of this contour had a mean minimum and maximum frequency of 2.5 kHz and 5.6 kHz (Faucher 1988). As with contours *2a* and 3*a*, contour 4*a* was shorter in Cook Inlet and Cunningham Inlet with a mean duration of 0.21 s and 0.45 s, respectively (Sjare and Smith 1986). The duration in Svalbard and the St. Lawrence Estuary fell between the two with an average duration of 0.37 s and 0.39 s respectively (Faucher 1988, Karlsen *et al.* 2002).

Contour types 5*a* and 5*b* are descending-ascending frequency whistles. Contour 5*a*, the unsegmented contour, would include the Cook Inlet calls within the Down-Up category with 1 inflection, including CI-10, CI-36, and CI-45 (Table A.1). The mean minimum frequency of this call contour was similar between Cook Inlet and Cunningham Inlet though the mean maximum frequency was approximately 1.2 kHz less in Cook Inlet than Cunningham Inlet (Sjare and Smith 1986). Calls within this contour in the St. Lawrence Estuary and Svalbard were emitted at higher frequencies than in Cook Inlet or Cunningham Inlet with mean minimum and maximum frequencies of 4.1 and 5.0 kHz in the St. Lawrence and 5.3 and 5.8 kHz in Svalbard (Faucher 1988, Karlsen *et al.* 2002). Mean call durations were also similar between the four locations (Sjare and Smith 1986, Faucher 1988, Karlsen *et al.* 2002).

Contour types 6*a*, 6*b*, and 6*c* are wavering frequency whistles. Type 6*a* wavers regularly whereas 6*b* has irregular wavering. Type 6*c* is segmented. Contours with more than 1 inflection point belong to this group of contours. Contours CI-24, CI-47, and CI-67 (Table A.1) belong to contour 6*a*. Mean minimum and maximum frequencies for this contour in Cook Inlet were 4.2 and 4.9 kHz, very similar to the St. Lawrence Estuary (Faucher 1988). In Cunningham In let mean minimum and maximum frequencies for this contour were 3.3 and 4.3 kHz (Sjare and Smith), lower than in Cook Inlet and the St. Lawrence. Mean call duration was shorter in Cook Inlet (0.81 s) than Cunningham Inlet (1.00 s) or the St. Lawrence (1.43 s) (Sjare and Smith 1986, Faucher 1988). Contours CI-12, CI-15, CI-19, CI-26, CI-44, , CI-49, CI-52, CI-54, CI-56, CI-59, CI-64, CI-66, CI-69, CI-71, CI-73, CI-74, CI-76, CI-77, CI-78, CI-80, CI-81, CI-82, CI-83, CI-84, CI-85, CI-88, CI-89, and CI-90 (Table A.1) belong to contour 6*b*. Mean minimum frequencies for this contour were similar between Cook Inlet and Cunningham Inlet, but the mean maximum frequency in Cook Inlet was approximately 1.2 kHz below the mean maximum frequency in Cunningham Inlet. In the St. Lawrence Estuary, mean minimum and maximum frequencies for this contour were 2.5 and 9.2 kHz (Faucher 1988). Durations of calls within this contour were dramatically shorter in Cook Inlet than Cunningham Inlet or the St. Lawrence Estuary with mean durations of 0.37 s compared to 1.25 s and 1.79 s (Sjare and Smith 1986, Faucher 1988). Contours 6*a* and 6*b* were grouped together in the Karlsen *et al.* (2002) study with a mean minimum and maximum frequency of 5.2 and 6.8 kHz and mean duration of 1.06 s (Karlsen *et al.* 2002).

The final whistle contour defined by Sjare and Smith (1986) was contour 7, the trill whistle, which was emitted in series. Cook Inlet contours CI-2 and CI-51 (Table A.1) can be grouped into this contour. In Cook Inlet, these calls were generally emitted below 2 kHz, but in

Cunningham Inlet and the St. Lawrence Estuary, the mean frequency of these calls was 5.9 kHz and 6.8 kHz respectively (Sjare and Smith 1986, Faucher 1988). The duration of these calls could not be compared because in Cook Inlet the duration of each individual call was measured whereas in Cunningham Inlet and the St. Lawrence Estuary, the duration of the series was measured. This contour was not identified in Svalbard.

All the whistle contours identified in Chapter 1 could be grouped into the classification scheme of Sjare and Smith (1986), though the segmented contours in Sjare and Smith's study, 1*b*, 2*b*, 3*b*, 3*c*, 3*d*, 4*b*, 5*b*, and 6*c* (1986), could not be identified in Cook Inlet as they were treated as separate calls. While the contours 1*a*, 2*a*, 3*a*, 4*a*, 5*a*, 6*a*, 6*b*, and 7 (Sjare and Smith 1986) were identified in Cook Inlet, most frequency characteristics and duration measurements differed from those in Cunningham Inlet, the St. Lawrence Estuary, and Svalbard (Sjare and Smith 1986, Faucher 1988, Karlsen *et al.* 2002) with belugas in Cook Inlet generally utilizing lower frequencies than belugas in the other three locations. Due to the broad definition of contours 6*a* and 6*b*, it was not possible to determine if there were contours unique to Cook Inlet that had not been previously observed in Cunningham Inlet, the St. Lawrence Estuary, or Svalbard.

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Karlsen, J., A. Bisther, C. Lydersen, T. Haug and K. Kovacs. 2002. Summer vocalisations of adult male white whales (*Delphinapterus leucas*) in Svalbard, Norway. Polar Biology 25:808-817.

Sjare, B. and T. Smith. 1986b. The acoustic repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. Canadian Journal of Zoology 64:407-415.

Table A.1 Cook Inlet Beluga Whistle Contours

Characteristics and descriptive statistics of whistle contours used by Cook Inlet beluga whales. Contours are numbered based upon how frequently they were used. Contours are grouped based on their beginning and ending frequency slope. The overall frequency trend (ascending – ending frequency greater than ending frequency; descending – ending frequency less than beginning frequency; neutral – ending frequency and beginning frequency approximately equal), and the number of inflections (Inf.) are also presented. Mean (SD) beginning frequency, ending frequency, minimum frequency, maximum frequency, and duration are presented for those contours with a statistical sample size (statistical n) greater than 3.

Up-Down (n = 313)

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.	Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
CI-1	119	73	8	38	Neutral	1	3702 (3215)	3811 (3502)	3410 (3072)	4068 (3598)	0.30 (0.17)	31
CI-4	79	39	2	38	Ascending	1	1678 (1660)	1715 (1652)	1627 (1573)	1813 (1790)	0.37 (0.39)	28
CI-18	26	12	0	14	Descending	1	1861 (2130)	1877 (2258)	1831 (2145)	1959 (2309)	0.16 (0.07)	9
CI-53	6	2	0	4	Neutral	1	6818 (2049)	6091 (2093)	5927 (2188)	7312 (1938)	0.65 (0.40)	4
CI-57	5	2	0	3	Descending	1	3699	2722	2722	4004	0.46	2
CI-68	4	2	0	2	Descending	1	7337	7642	7153	7654	0.58	2
CI-86	2	1	1	0	Descending	1	7629	7678	7385	7898	0.34	2
CI-87	2	2	0	0	Descending	1	6470	6873	6067	7215	0.52	2
CI-24	20	13	1	6	Ascending	3	5195 (3923)	5391 (3972)	5195 (3923)	5430 (3999)	0.14 (0.05)	5

Table A.1 continued…

CI-26	18	11	3	4	Ascending	3	662 (151)
CI-47	7	3	1	3	Neutral	3	8691
CI-54	5	3	0	2	Descending	3	989
CI-66	4	3	1	0	Ascending	3	5438 (3645)
CI-73	3	0	0	3	Ascending	3	7629
CI-76	3	3	0	0	Ascending	3	6982
CI-59	5	3	0	2	Descending	5	8211
CI-89	2	2	0	0	Descending	5	
CI-69	3	3	0	0	Neutral	15	

Down-Down (n = 196)

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.	Beg. Freq. (Hz)
CI-6	67	13	1	53	Descending	0	3764 (3766)
CI-16	31	14	0	17	Descending	0	4700
CI-51	6	4	2	0	Descending	0	
CI-58	5	2	0	3	Descending	0	4150
CI-72	3	0	3	0	Descending	0	2881
CI-15	33	28	0	5	Descending	2	7247 (671)

860	652	867	0.26	10
(335)	(153)	(330)	(0.17)	
8618	7935	9155	0.81	1
1050	891	1050	0.25	2
5622	4846	5915	0.64	4
(3290)	(3053)	(3477)	(0.36)	
7959	7312	8496	0.25	2
7520	6982	8057	0.48	1
8569	8032	8594	0.24	3

End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
3889	3382	4222	0.42	5
(3727)	(3452)	(3986)	(0.32)	
5139	4700	5457	0.14	2
4142	4069	4289	0.29	3
2783	2620	3214	0.44	3
6339	6156	7312	0.49	5
(349)	(291)	(561)		

Table A.1 continued…

CI-19	26	12	1	13	Descending	2	6057 (2081)
CI-52	6	4	0	2	Descending	2	4712
CI-64	4	1	1	2	Descending	2	1502
CI-48	7	4	0	3	Neutral	4	4193 (2647)
CI-67	4	2	0	2	Descending	4	1978
CI-84	2	1	1	0	Descending	4	3174
CI-85	2	0	2	0	Descending	4	3980

Down-Up (n = 177)

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.	Beg. Freq. (Hz)
CI-2	91	47	10	34	Neutral	1	3964 (3371)
CI-10	42	28	1	13	Ascending	1	3441 (3443)
CI-36	12	7	0	5	Neutral	1	5386 (3094)
CI-45	8	4	0	4	Descending	1	1795
CI-44	8	3	0	5	Neutral	3	7088
CI-49	7	3	0	4	Neutral	3	1733
CI-88	2	1	0	1	Neutral	3	3967
CI-80	2	2	0	0	Descending	5	

5876	5559	6457	0.48	17
(2136)	(2186)	(2087)	(0.41)	
5188	4700	5225	0.28	2
1611	1502	2442	0.38	2
4047	3937	4224	0.42	4
(2579)	(2564)	(2595)		
1733	1685	2441	1.15	1
3027	3027	3198	0.63	1
4114	3845	4602	0.42	2

End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
4098	3839	4263	0.31	8
(3478)	(3334)	(3548)	(0.24)	
3545	3340	3714	0.51	24
(3426)	(3330)	(3502)	(0.39)	
5525	5244	5627	1.05	9
(3199)	(2958)	(3298)	(0.81)	
2039	1770	2136	0.43	2
6087	6014	7186	0.65	3
1880	1636	2075	0.35	1
3931	3711	4261	0.92	2

Table A.1 continued…

CI-77	3	2	0	1	Ascending	7
CI-90	2	2	0	0	Ascending	17

Up-Up (n =

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.
CI-9	49	28	1	20	Ascending	0
CI-28	17	11	0	6	Ascending	0
CI-33	13	9	3	1	Ascending	0
CI-35	12	5	0	7	Ascending	0
CI-39	10	4	0	6	Ascending	0
CI-40	10	5	0	5	Ascending	0
CI-43	8	1	0	7	Ascending	0
CI-65	4	1	2	1	Ascending	0
CI-12	37	22	0	15	Ascending	2
CI-56	5	1	2	2	Ascending	2
CI-82	2	2	0	0	Ascending	4
CI-71	3	0	1	2	Ascending	4
CI-74	3	2	0	1	Ascending	4

6824	6885	6226	6934	0.58	2
2869	3064	2698	3076	0.61	2

= 176)

Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
3598	3849	3571	4002	0.15	14
(2291)	(2311)	(2241)	(2454)	(0.07)	
6182	6152	5930	6597	0.52	6
(2237)	(2138)	(2225)	(2194)	(0.29)	
2333	2563	2323	2570	0.27	7
(2358)	(2603)	(2354)	(2600)	(0.19)	
5811	6380	5737	6454	0.14	3
4578	4187	4187	4578	0.17	2
7874	6775	6690	7874	0.28	2
2602	2434	2382	2658	0.27	16
(2218)	(2221)	(2180)	(2236)	(0.13)	
4045	4240	4045	4508	0.27	3
7715	8423	7715	8472	1.46	1
7080	6934	6779	7340	0.74	3

Table A.1 continued…

CI-78	3	3	0	0	Neutral	14	2015	1990	1990	2015	0.18	2

Flat-Flat (n = 81)

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.	Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
CI-3	81	34	6	41	Neutral	0	1416 (812)	1461 (837)	1397 (821)	1490 (833)	0.57 (0.50)	22

Down-Flat (n = 79)

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.	Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
CI-5	73	31	4	38	Descending	0	4169 (1942)	3854 (1939)	3645 (1943)	4497 (1910)	0.75 (0.45)	13
CI-62	4	2	0	2	Descending	0	4138	3589	3589	4138	0.18	2
CI-91	2	0	0	2	Ascending	1						

Flat-Down (n = 73)

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.	Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
CI-7	64	33	1	30	Descending	0	1639 (2330)	1587 (2164)	1529 (2169)	1660 (2322)	0.22 (0.09)	14
CI-61	4	3	1	0	Descending	0	789	855	757	855	0.12	3
CI-81	2	1	0	1	Ascending	2	1807	1831	1733	1831	0.20	1
CI-83	2	1	1	0	Descending	5						

Table A.1 continued…

Up-Flat (n =

Contour	# Obs.	EBS n	TBS n	TBW n	Freq. Trend	Inf.
CI-22	21	11	1	9	Ascending	0
CI-38	10	7	0	3	Ascending	0
CI-25	19	7	0	12	Descending	1

= 50)

Beg. Freq. (Hz)	End. Freq. (Hz)	Min. Freq. (Hz)	Max. Freq. (Hz)	Duration (s)	Statistical n
1465	1370	1364	1486	0.50	8
(854)	(771)	(777)	(853)	(0.42)	
1115	1196	1115	1196	0.31	3
2832	2947	2790	3104	0.48	7
(2844)	(2962)	(2869)	(2984)	(0.29)	

Chapter 2 : Underwater Ambient Sound Levels in Trading Bay and Eagle Bay in Cook Inlet, Alaska and Possible Implications for Beluga Whales[1]

Abstract

Cook Inlet, Alaska is a semi-enclosed estuary in south central Alaska fed at its northern end by several glacial rivers. The inlet is dominated by strong tidal regimes, and its watershed is home to 2/3 of Alaska's human population. Several commercially important species of fish and invertebrates and species of marine mammals reside in Cook Inlet including an endangered population of beluga whales. This study made opportunistic use of passive acoustic monitoring data collected as part of a beluga monitoring project to measure ambient sound levels in two locations in Cook Inlet and to determine if ambient sound levels preceding and following beluga acoustic encounters in these locations varied significantly which could suggest noise influences beluga movements in these areas. Bottom-moored hydrophones were deployed at Eagle Bay in summer 2009 and at Trading Bay in summer and winter 2009. The hydrophones sampled at 25 kHz with a 10% duty cycle, recording 30 seconds of every 5 minutes. One 30-second file per hour during the sampling period, July – September for the summer and December – February for the winter, was randomly selected for analysis. A one-third octave band analysis was conducted with central band frequencies ranging from 100 Hz to 8 kHz. A multivariate analysis of variance was conducted on the one-third octave root mean square (RMS) sound pressure levels (SPLs) to examine for variation between seasons. The highest RMS SPLs were recorded in the 100 Hz band. Root mean square SPLs were found to vary significantly both seasonally and spatially with greater ambient noise levels in the summer than in the winter for frequencies above 500 Hz. These differences are likely due to increased small vessel traffic and oil and gas development

[1] Blevins, R., S. Atkinson, and M. Lammers. Underwater ambient sound levels in Trading Bay and Eagle Bay in Cook Inlet, Alaska and possible implications for beluga whales. Formatted for *Marine Mammal Science*

activities in the summer compared to the winter. Comparisons of ambient sound levels preceding and following beluga acoustic encounters with general ambient sound levels in these areas did not suggest belugas were leaving the area due to noise. Some RMS SPLs measured in this study may be sufficient to mask signals of marine mammals in Cook Inlet, including beluga whales. Measured sound levels may also affect ecologically and commercially important fish and invertebrate species in the inlet.

Introduction

Sound is transmitted very efficiently in water, and ambient noise, defined as "the sound field against which signals must be detected" (Hildebrand 2009), is an important characteristic of the marine environment. Ambient noise in the marine environment is generally classified into low frequency (10 – 500 Hz), mid frequency (500 Hz – 25 kHz), and high frequency (over 25 kHz) bands (Hildebrand 2009). High frequency noise was not recorded as part of this study and will not be considered in this work. While low frequency sounds have very low attenuation in deep water environments, in shallow environments such as Cook Inlet the long wavelengths of low frequency sounds severely limit their propagation. Mid-frequency noise propagates over regional scales (tens of kilometers) (Hildebrand 2009).

Both natural and anthropogenic sound sources contribute to the ambient noise environment. Natural ambient noise is generated by both physical processes and organisms. In Cook Inlet, physical processes that contribute to ambient noise include wind, precipitation, sea ice movement, and changing tides. Generally breaking waves caused by wind is the dominant source of underwater noise in the mid-frequency band (Franz 1959, Ma *et al.* 2005); precipitation is another natural source of noise in the mid-frequency band (Franz 1959, Ma *et al.* 2005). Underwater noise can also be created as changing tides generate currents that can lead to flow noise. An additional source of noise, sea ice can lead to an increase in low frequency noise from increased tidal turbulence (Blackwell and Greene 2002). While sea ice generates underwater noise, it also has the potential to dampen ambient noise by reducing or eliminating noise from sea surface agitation (Milne and Ganton 1964). Sound produced by marine species is another natural source of underwater noise in Cook Inlet. Fish generate low-frequency sounds between 50 Hz and 2 kHz, primarily between 100 and 500 Hz (Zellick and Mann 1999, Myrberg and

Fuiman 2002). Marine mammals also produce a variety of sounds spanning from mysticete low-frequency calls to odontocete high-frequency echolocation signals (Richardson *et al.* 1995).

Humans have been a source of noise in the marine environment since the transition from wind-driven to mechanized shipping (NRC 2005). Sources of anthropogenic noise in Cook Inlet include large vessel traffic, seismic surveys, oil rig operation, small boat activity, fish-finding sonar, dredging, marine construction, and jet overflights from Anchorage International Airport and Joint Base Elmendorf-Richardson. Generally the most significant contributors to low frequency ambient noise are commercial shipping and seismic exploration (Richardson *et al.* 1995). These activities occur in Cook Inlet, but water depth in the inlet limits transmission of such low frequency sounds. Oil drilling and pile driving, often part of marine construction, also emit high acoustic energy at low frequencies (Greene 1987). In the mid-frequency band, small vessels generate noise in Cook Inlet (Richardson *et al.* 1995). Sonar generates noise in all frequency bands. Sonar used for fish-finding utilizes high frequency sound, but rapid attenuation probably limits its impact to localized scales (Hildebrand 2009). Explosions, generally used in construction and demolition, generate broadband noise with high source levels (Richardson *et al.* 1995). Jets also generate broadband noise though of relatively short duration compared to the duration of audibility in air (Smith 1989).

Many marine species have evolved to utilize sound. Marine mammals rely on sound to communicate, navigate, and hunt (Au 1993, Edds-Walton 1997, Wartzock and Ketten 1999). Fish and some invertebrates use sound to navigate, communicate, and select habitat (Bass and McKibben 2003, Simpson *et al.* 2005). Hearing abilities in marine organisms vary between groups and species (Table 2.1). Baleen whales' hearing capabilities have never been studied directly, but the frequency of their phonations and hearing physiology suggests that they have

evolved to hear low frequencies (Ketten 1992). Odontocetes have acute mid-frequency hearing and have good perception at high frequencies utilized for echolocation (Richardson *et al.* 1995). Teleost fish are grouped into hearing specialists and hearing generalists: specialists have good hearing from 300-1000 Hz while generalists have good hearing from 100-400 Hz (Popper 2003). Sound reception in invertebrates is not well studied, but prawns detect sound from 100 Hz to 3 kHz (Lovell *et al.* 2005).

Ambient noise can affect organisms through behavioral disturbance, physical injury, or masking. Marine mammal reactions to noise disturbance are highly variable and context-specific (Richardson *et al.* 1995). Exposure to intense sound can lead to temporary or permanent hearing loss in marine mammals. Masking can occur when the frequency of ambient noise overlaps an organism's hearing frequencies (Figure 2.1, Table 2.1). Masking occurs when a sound prevents an organism from detecting another signal such as a conspecific call (Foote *et al.* 2004). Some marine mammal species can compensate for the effects of masking by changing the frequency or source level of their acoustic emissions, repeating their signals, or altering the timing of their signals to increase the chances the call will be detected by conspecifics (Lesage *et al.* 1999, Foote *et al.* 2004, Morisaka *et al.* 2005, Holt *et al.* 2009). However, these techniques may have metabolic costs (Jensen *et al.* 2009). Studies of the effects of sound on fish are relatively few, but potential impacts of sound on fish are similar to those of marine mammals. Behavioral responses of fish to noise range from a startle response (Wardle *et al.* 2001) to displacement (Slotte *et al.* 2004). Noise exposure can lead to hearing loss in fishes (Hastings *et al.* 1996) or mask important acoustic signals (Wysocki *et al.* 2006). Noise may also stress fish, as some fish species have exhibited increased cortisol secretion following exposure to ship noise (Wysocki *et al.* 2006). The issue of underwater noise may worsen in coming years due to

increased human activity in the marine environment. There is also a potential for increased propagation of low frequency sound in some areas due to ocean acidification (Hester *et al.* 2008).

Ambient noise levels may be important to the organisms inhabiting Cook Inlet, Alaska. The inlet is home to several species of marine mammals including beluga whale *Delphinapterus leucas*, as well as harbor seal *Phoca vitulina*, Steller sea lion *Eumetopias jubatus*, harbor porpoise *Phocoena phocoena*, Dall's porpoise *Phocoenoides dalli*, killer whale *Orcinus orca*, grey whale *Eschrichtius robustus*, minke whale *Balaenoptera acutorostrata*, and humpback whale *Megaptera novaeangliae* (80 FR 29162). The beluga population in Cook Inlet experienced a dramatic decline between 1994 and 1998 leading to its depleted listing under the Marine Mammal Protection Act in 1999. The population failed to show signs of recovery in the following years and was listed as endangered under the Endangered Species Act in 2008 (73 FR 62919). Cook Inlet also supports commercial, personal use, and subsistence fisheries for Pacific salmon *Oncorhynchus spp.*, Pacific herring *Clupea pallasii*, Pacific cod *Gadus macrocephalus*, sablefish *Anoplopoma fimbria*, lingcod *Ophiodon elongatus*, rockfish *Sebastes spp.*, halibut *Hippoglossus stenolepis*, walleye pollock *Gadus chalcogrammus*, tanner crab *Chionoecetes bairdi*, Dungeness crab *Metacarcinus magister*, and other invertebrate species (Trowbridge and Goldman 2006, Russ *et al.* 2013). Many of these species are prey for beluga whales (Huntington 2000, NMFS 2015). It is important to understand the ambient sound levels in Cook Inlet to understand their potential impact on the species living there including the endangered Cook Inlet beluga (CIB) population.

This study made opportunistic use of passive acoustic monitoring with the objective of measuring underwater ambient sound levels in Eagle Bay and Trading Bay in Cook Inlet, Alaska

(Figure 2.2) where beluga acoustic behavior has been previously studied (Blevins 2015). Measuring ambient noise levels will provide a better understanding of the background noise with which belugas and other inhabitants of Cook Inlet must cope. Broadband noise levels were previously measured at several locations in Cook Inlet, including Eagle Bay, in 2001 (Blackwell and Greene 2002) shortly after the decline of the CIB population, but no measured noise levels have been reported since that time. Ambient sound levels have not been previously reported for Trading Bay. Another objective of this study was to compare the ambient underwater noise levels between time periods preceding and following acoustic encounters with beluga whales to look for any evidence of noise influencing beluga movements into or out of Eagle Bay and Trading Bay. Data necessary to model sound propagation in Cook Inlet was not collected as part of this study, and a characterization of the acoustic properties of the environment in Eagle Bay and Trading Bay lies outside the scope of this work.

Methods

Site selection

Cook Inlet is a semi-enclosed tidal estuary in south-central Alaska at 60.34° N and 151.88° W (Figure 2.2). It is approximately 370 km long and 32 km wide. It is fairly shallow, not exceeding 60 m deep in most places. Several major rivers, including the Susitna, Matanuska, and Knik, flow into the inlet at the northern end depositing a large amount of glacial silt. Cook Inlet is dominated by strong tidal regimes with a typical range of 9 meters per day, the largest in the United States and second in the world only to the Bay of Fundy (Mulherin *et al.* 2001). Sea ice is present in Cook Inlet from October or November through March or April (Mulherin *et al.* 2001). The Cook Inlet watershed is home to 400000 residents, approximately 2/3 of Alaska's human population (Cook Inlet Keeper 2015, see www.inletkeeper.org/about/watershed). Cook

Inlet is the main route for bringing ocean-transported cargo into Alaska (Okkonen *et al.* 2009) and supports commercial, personal use, and subsistence fisheries. A number of active oil rigs are present in Cook Inlet, and seismic surveys are ongoing for potential future oil and gas development.

This study made opportunistic use of acoustic recordings collected by the Cook Inlet Beluga Acoustic (CIBA) project, a passive acoustic monitoring project to document habitat usage by CIB. Two sites from the CIBA project, Eagle Bay and Trading Bay (Figure 2.2), were chosen for this study to contrast the ambient sound levels at two locations known to be important for CIB and where CIB calling behavior has been previously studied (Blevins 2015). Eagle Bay was selected as the upper inlet location and lies within the CIB Critical Habitat Area 1 (76 FR 20180). It is located north of Anchorage in Knik Arm (Figure 2.2) and is near a high population density of humans from Anchorage. There is a nearby military base, Joint Base Elmendorf-Richardson, with aircraft that generate aerial noise that is detectable underwater (Lammers *et al.* 2013). The water is shallow and visibility is limited due to the high load of glacial silt carried into the bay from Eagle River. Eagle River, which terminates at Eagle Bay, serves as salmon spawning habitat for all five Pacific salmon species during the summer season (ACE 2013), and is exploited by CIB as a summertime foraging habitat. Trading Bay, located within the CIB Critical Habitat Area 2 (76 FR 20180), was selected to represent the mid inlet and the southern end of the current CIB range. It is a wide bay located immediately north of the West Foreland and fed by the McArthur River (Figure 2.2). Trading Bay is further from human population centers than Eagle River, but there are several oil rigs in the area and ships transit past Trading Bay en route to Anchorage.

Data collection

Ecological Acoustic Recorders (EARs), bottom-moored autonomous recorders described in Lammers *et al.* (2008), were configured as specified in Lammers *et al.* (2013). The EARs were deployed in Eagle Bay during summer 2009 for 47 days, in Trading Bay in summer 2009 for 94 days, and in Trading Bay in winter 2009-2010 for 83 days (Table 2.2, Figure 2.2) as part of a larger CIB study (Blevins 2015, Lammers *et al.* 2013). They were designed specifically to withstand environmental conditions in Cook Inlet (Lammers *et al.* 2013). The EARs were programmed to record on a 10% duty cycle, recording 30 seconds of every 5 minutes. This duty cycle was selected to capture phonations of belugas milling or traveling through the EARs' listening range over a minimum period of 10-20 minutes. Although the beluga detection range was not tested for the EARs at Eagle Bay or Trading Bay, an informal test of the EARs' listening range in Cook Inlet was previously conducted (Lammers *et al.* 2013). A signal (15-20 kHz frequency modulated sweep) was projected at a source level of 140 dB re 1 μPa; for which, the EAR was suspended at 3 m depth below a stationary vessel, and the projector was suspended at 2-4 m depth below a moving vessel. The sweep was projected at several distances from the EAR, and the maximum detection range varied from 2.2 to 3.3 km (Lammers *et al.* 2013). The EARs were set to sample at 25 kHz. Low frequency roll off occurred around 17 Hz, and the anti-aliasing filter was set to 80% of the sampling frequency providing an effective bandwidth of approximately 10 kHz.

Data analysis

The ambient sound levels were measured in Eagle Bay July-August 2009 and in Trading Bay July-September 2009 and December 2009-February 2010. One 30 second recording was randomly selected from each hour sampled for analysis. Files with flow noise and noise

generated by the EARs were excluded to avoid such contamination. Files with beluga calls were also excluded from the ambient noise analysis. To compare the pre- and post-beluga encounter ambient sound levels, the twelve files (spanning one hour) leading up to a beluga encounter and the twelve files following beluga encounters were also analyzed for the 39 beluga encounters recorded during the sampling period. For this study, an encounter was defined as a period of beluga acoustic activity separated from other phonations by more than 60 minutes. A one-third octave band analysis was conducted in Matlab (MATLAB Release 2013b, The MathWorks, Inc.) measuring the root mean square (RMS) sound pressure level (SPL) for the American National Standards Institute standard one-third octave bands with center frequencies 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, 6300, and 8000 Hz. SPLs were measured using the standard underwater reference pressure, 1 μPa.

Multivariate analysis of variance (MANOVA) was used to compare the one-third octave RMS SPLs from Trading Bay summer (TBS) and Trading Bay winter (TBW) to determine if the acoustic environment varied seasonally. If comparisons were found to be significant ($p < 0.05$), analysis of variance (ANOVA) was conducted on individual one-third octave bands to determine at which frequencies the differences occurred.

Multivariate analysis of variance was conducted on one-third octave RMS SPLs from the pre- and post-encounter files ($n = 538$) to determine if the pre- and post-beluga encounter ambient noise environments differed from each other. If comparisons were found to be significant ($p < 0.05$), ANOVA was conducted on individual one-third octave bands to determine at which frequencies the differences occurred. Multivariate analysis of variance was conducted on one-third octave RMS SPLs from the pre- and post-encounter files with time before or after the encounter (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, or 60 minutes) as a predictor to determine

if the ambient sound levels changed approaching or following a beluga encounter. Multivariate analysis of variance was conducted on one-third octave RMS SPLs from the pre-encounter files, post-encounter files, and the remaining ambient sound files to determine if the pre- and post-beluga encounter ambient sound levels differed from the general ambient sound levels at these locations. If comparisons were found to be significant ($p < 0.05$), ANOVA was conducted on individual one-third octave bands to determine at which frequencies the differences occurred. If the ANOVA was significant, Tukey's HSD test (Tukey 1949) was performed.

Six minute tide levels for Anchorage (Station ID: 9455920) were obtained from NOAA NOS Center for Operational Oceanographic Products and Services (tidesandcurrents.noaa.gov). The differences in tide level were calculated and used as a proxy for current. Based on the time of the recordings, the files were paired with the appropriate current proxy, and a linear regression against RMS SPLs was performed in R (R Core Team 2015). A cross correlation was performed to check for lag effects.

Results

Root mean square SPLs showed high variation between frequency bands and within frequency bands (Figure 2.3). In the one-third octave analysis, the lowest RMS SPL was recorded in TBS where the measurements ranged from 42.1 to 117.1 dB re 1 µPa (Figure 2.4, Table 2.3). The highest RMS SPLs were recorded in EBS where the measurements ranged from 42.4 to 128.7 dB re 1 µPa (Figure 2.4, Table 2.3). The one-third octave band RMS SPLs ranged from 43.2 to 106.5 dB re 1 µPa in TBW (Figure 2.4, Table 2.3). Across all three datasets the lowest one-third octave ambient levels were recorded in the 200 Hz band and the highest were in the 100 Hz band (Figure 2.4, Table 2.3).

The results of the MANOVA showed that mean RMS SPLs varied seasonally ($p < 0.001$) (Figure 2.5). Analysis of variance on individual one-third octave bands showed that mean one-

third octave RMS SPLs varied significantly across all frequency bands ($p < 0.005$) except the 400 Hz band ($p = 0.31$). Mean RMS SPLs were higher in the winter for the frequency bands up to 315 Hz and higher in the summer for the frequency bands at or above 500 Hz. The greatest differences in mean SPLs occurred in the 2.5 and 3.15 kHz bands (6.0 and 4.3 dB re 1 μPa respectively).

Multivariate analysis of variance showed the pre- and post-beluga encounter ambient sound levels were significantly different ($p < 0.001$). Analysis of variance with individual one-third octave bands showed that mean RMS SPLs varied significantly in the 100 ($p = 0.026$), 125 ($p = 0.026$), 160 ($p = 0.027$), 315 (0.020), 400 ($p = 0.044$), 500 ($p = 0.015$), and 630 ($p = 0.045$) Hz bands with mean pre-encounter RMS SPLs higher than mean post-encounter RMS SPLs. The greatest differences occurred in the 100, 125, and 160 Hz bands. There was no relationship between time before or after beluga encounter and RMS SPL ($p = 0.77$). Multivariate analysis of variance also showed that pre-encounter, post-encounter, and general ambient sound levels differed significantly ($p < 0.001$). Analysis of variance results indicated that the mean RMS SPLs varied significantly ($p < 0.005$) across all frequency bands except 3.15, 4, and 5 kHz. General ambient sound levels were higher than pre- and post-encounter levels for bands up to 2.5 kHz. Pre- and post-encounter ambient sound levels were higher than general ambient sound levels in the 6.3 and 8 kHz bands.

The regression showed no relationship between tide and SPL ($R^2 < 0.05$ for all frequency bands). The cross correlation analysis did not reveal any significant lag effects.

Discussion

There was substantial variation in the ambient noise levels in Cook Inlet. The highest levels occurred in the 100 Hz one-third octave band. Generally, the dominant source of ambient

noise at this frequency arises from commercial shipping (Ross 1976). As Cook Inlet serves as the primary route to bring ocean-transported cargo into Alaska, regular shipping traffic would be expected to transit through the inlet. However, given the long wavelength of sounds within this frequency band and the shallow depth of Cook Inlet, sounds at these frequencies would attenuate rapidly. This suggests that the sources generating such noise are near the EARs. Noise from operating oil rigs could also contribute to sound levels within this frequency band as such noise peaks around 80 Hz (Blackwell and Greene 2002). A previous study in Cook Inlet showed that sound measurements from an oil rig were highest at 1.2 km from the platform and diminished to background levels at 19 km from the platform (Blackwell and Greene 2002) indicating that oil rig noise would likely be detectable on the Trading Bay EAR. While the RMS SPLs recorded in the 100 Hz one-third octave band reached 109.56 dB re 1 μPa, mean RMS SPLs in this band ranged from 74.16 dB re 1 μPa in EBS to 82.96 dB re 1 μPa in TBW (Table 2.3). Despite having the highest measured RMS SPLs, the sound levels in this frequency band are unlikely to affect CIB as the beluga hearing threshold at 100 Hz is approximately 125 dB re 1 μPa (White *et al.* 1978, Awbrey *et al.* 1988), greater than the maximum recorded RMS SPL in this study. However, it is possible, if source levels are sufficiently high, that received levels at greater proximity to the sound source may exceed the hearing threshold of beluga whales which would make the sound detectable for them.

The mean RMS SPLs in this study were lower than those previously reported for Eagle Bay where the mean broadband (20 Hz – 1 kHz) RMS SPL was 107.2 dB re 1 μPa (Blackwell and Greene 2002). However, comparisons between these values are limited as this study measured RMS SPLs within one-third octave bands, and the previous study measured broadband RMS SPLs. Broadband RMS SPLs tend to be higher than one-third octave RMS SPLs as sound

levels are a summation across the frequencies contained within the measured band and broadband levels cover a wider frequency band than one-third octaves.

In this study, mean RMS SPLs at frequencies of 1 kHz or less were below 65 dB re 1 μPa with the exception of the 100 Hz and 125 Hz one-third octave bands (Table 2.3, Figure 2.4). Anthropogenic noise generally dominates ambient sound levels at these frequencies. The RMS SPLs at or below 1 kHz measured in this study are unlikely to cause masking for CIB. Hearing thresholds for beluga whales at frequencies below 1 kHz exceed 100 dB re 1 μPa (White *et al.* 1978, Awbrey *et al.* 1988). Unless belugas are close to the source emitting noise at these frequencies, it is unlikely they would be able to detect the sound. Sound levels at these frequencies may be more substantial in other areas of Cook Inlet. A previous study of ambient noise in Cook Inlet showed there was an increase in broadband RMS SPL of approximately 20 dB re 1 μPa at industrial sites compared to the more remote sites which included Eagle Bay (Blackwell and Greene 2002). While this increase may not be sufficient to exceed beluga hearing thresholds at these frequencies, it could be important for other species in the inlet with greater low-frequency hearing sensitivity including baleen whales, fish, and invertebrates.

Ambient sound levels were significantly higher in the summer than the winter at Trading Bay for the frequency bands of 500 Hz and higher. This is likely due to increased human activity in the inlet during the summer months. The largest differences in mean SPL occurred in 2.5 and 3.15 kHz bands (Figure 2.5) where small vessel noise occurs. The presence of sea ice which forms in Cook Inlet beginning in October or November and lasts until March or April (Mulherin *et al.* 2001) limits travel of small vessels during the winter. Along with improved weather conditions, the presence of anadromous fish also contributes to increased vessel traffic during the summer months.

Despite winter ice coverage, there was no definitive ice noise detected in this study. When ice is present there is the potential for an increase in low frequency ambient noise due to increased turbulence from tidal flow (Blackwell and Greene 2002). This may have contributed to the significantly higher mean RMS SPLs in the frequency bands from 100 to 315 Hz in the winter than the summer. The presence of sea ice can also lead to an increase in high-frequency noise created by thermal cracking of ice (Milne and Ganton 1964). Such noise was not unambiguously observed in the data. However, there was only one hydrophone recording during the winter which limited winter sampling. The increase in RMS SPLs in the 2.5 and 3.15 kHz bands in the summer would be more likely to impact CIB than the increase in low frequency RMS SPLs in the winter as belugas have greater hearing sensitivity at these higher frequencies. At 3 kHz the beluga hearing threshold is approximately 80 dB re 1 μPa (White *et al.* 1978, Awbrey *et al.* 1988). While this threshold exceeds mean RMS SPLs in these frequency bands, sound levels approaching the maximum recorded RMS SPLs would be audible to belugas.

Seasonal differences in measured SPL levels could also be due to physical differences in the environment leading to differences in sound propagation. Data necessary to measure or model sound propagation was not collected as a part of this study. Therefore a comparison of the physical environment between summer and winter and an evaluation of how such differences would affect sound propagation is beyond the scope of this project.

The low R^2 of the regression of tidal current against noise suggests tidal flow noise around the EARs was likely successfully eliminated from our analysis. Flow noise was excluded from the analysis because the relatively stationary presence of the moored hydrophone was assumed to artificially increase the level of flow noise measured and its exclusion is recommended when attempting to measure ambient noise (Richardson *et al.* 1995). However, this does not indicate

that current noise is not a considerable source of ambient noise in Cook Inlet. Rather, tides in the inlet vary by approximately 9 meters per day making them the most extreme in the United States (Mulherin *et al.* 2001) and currents within the inlet can reach 6.2 m/s (Moore *et al.* 2000). Tidal noise likely makes up a substantial component of ambient background noise at certain times in Cook Inlet.

While there was a significant difference in pre- and post-beluga encounter sound levels in the lower frequency bands, pre-encounter sound levels were higher than post-encounter levels indicating that belugas were likely not driven from the areas by noise. Both the pre- and post-beluga encounter sound levels were significantly higher than the general sound levels in the uppermost frequency bands, where beluga hearing is more sensitive (White *et al.* 1978, Awbrey *et al.* 1988). The higher sound levels leading up to a beluga encounter suggest that CIB may be attracted to the areas by sound. Documented cases of beluga attraction to anthropogenic noise are few. In such cases the acoustic stimulus was novel, attraction occurred in only young belugas, and the period of attraction was short-lived (Blane 1990). However, other noise sources could be responsible for drawing belugas to these areas. In summer, CIB tend to prefer areas with medium to high flow (Goetz *et al.* 2007). Higher sound levels may be indicative of increased freshwater inflow at these times which may attract belugas. Movement of sediment in these areas could also increase sound levels. Disturbance of the bottom substrate could increase prey availability for belugas which consume some benthic prey including flounder, polychaetes, and crustaceans (NMFS 2015). Another possibility is sounds produced by beluga prey species could increase ambient sound levels. Such sounds would be expected to attract beluga whales to the area to forage.

Beluga whales can hear from 40 Hz (Johnson *et al.* 1989) up to 150 kHz (Au 1993) with their best hearing sensitivity between 10 and 100 kHz (White *et al.* 1978, Awbrey *et al.* 1988), indicating that they can hear over the entire range analyzed in this study. Across the frequencies analyzed in this study, beluga whale hearing is most acute in the 8 kHz band where the beluga hearing threshold is approximately 65 dB re 1 μPa (White *et al.* 1978, Awbrey *et al.* 1988). The 8 kHz band was the only band where mean RMS SPLs approached the hearing threshold for beluga whales. Maximum RMS SPLs at all frequencies above 2 kHz would be expected to be audible for beluga whales. While mean RMS SPLs in Eagle Bay and Trading Bay generally fell below beluga hearing thresholds, it is possible that sound levels in more industrialized areas of the inlet could exceed their hearing thresholds and potentially impact CIB. It is also possible that if belugas were in closer proximity to noise sources than the EARs in this study, the sound generated by the source may be detectable for the whales. This study sought only to measure ambient sound levels and did not attempt to measure sound generated by individual sources. Broadband sound levels of various anthropogenic sources were measured in a previous study in Cook Inlet in 2001. The loudest anthropogenic noise source recorded in this previous study was a tug boat docking a gravel barge which reached a broadband (10 Hz – 20 kHz) RMS SPL of 149 dB re 1 μPa (Blackwell and Greene 2002) which would be audible to beluga whales at frequencies above 100 Hz (White *et al.* 1978, Awbrey *et al.* 1988). The 2001 study also measured underwater sound generated by aircraft overflights. Noise from overflights at Anchorage International Airport and Elmendorf Air Force Base reached broadband (10 Hz – 20 kHz) RMS SPLs of 125 dB and 135 dB re 1 μPa, respectively (Blackwell and Greene 2002). These SPLs would be sufficient to be audible to beluga whales at frequencies above approximately 300 Hz (White *et al.* 1978, Awbrey *et al.* 1988). Despite Eagle Bay's proximity

to Joint Base Elmendorf-Richardson, no airplane overflight noise appeared in the recordings in the present study. The time period of audibility of aircraft is less underwater than in air due to the 13° critical angle necessary for sound to transmit from the air into the water (Smith 1989). Given the short duration of audibility of aircraft overflights underwater, analyzing only 30 seconds of every hour in this study limited detection of aircraft in Eagle Bay. While no aircraft were recorded in this study, the measurements from aircraft overflights in the 2001 study (Blackwell and Greene 2002) suggest that when aircraft noise is present in Eagle Bay it has the potential to be intense and cover a large frequency spectrum. The likely audibility of vessel and aircraft noise indicates these types of noise have the potential to affect CIB.

Given the RMS SPLs measured within the frequency band of the present study combined with belugas' hearing thresholds, critical ratios (Johnson *et al.* 1989), the amount by which a signal must exceed ambient noise levels to be audible, and directional hearing sensitivity (Penner *et al.* 1986), beluga whales may be less affected by masking than other marine mammal species in Cook Inlet. The baleen whales (minke whales, humpback whales, and gray whales) in Cook Inlet phonate and likely have acute hearing in the low frequency bands where measured RMS SPLs were highest. This reliance on low frequency sound may make baleen whales the marine mammal group most susceptible to the effects of masking in Cook Inlet.

Sound levels in Cook Inlet could affect belugas indirectly by affecting their prey species. The fish and invertebrates that comprise CIB diets can hear or detect frequencies up to 1 kHz (Table 2.1). They could be affected by noise in the highest amplitude one-third octave band, 100 Hz, which could mask their signals (Wysocki *et al.* 2006). Exposure to noise can also lead to damage to sensory cells in the ears of fish (i.e. Hastings *et al.* 1996) which could lead to decreased survival of individuals (Popper *et al.* 2003). Sound can also displace fish from an area

(Slotte *et al*. 2004) and may affect migration routes (Popper and Hastings 2009). Changes in fish survival or distribution could affect prey abundance or availability for CIB. Such changes could also impact commercial, personal use, or subsistence fisheries in Cook Inlet.

Ambient noise in Cook Inlet warrants further study. Future studies should include more locations in Cook Inlet, especially those subject to greater anthropogenic influence. Additional studies could also extend the frequency range sampled. In particular, the sources of low frequency noise should be studied further to gain a fuller understanding of potential effects of ambient noise on commercially and ecologically important fish and invertebrate species in Cook Inlet. This study is only the second published report of noise levels in Cook Inlet. Differences in methodology prevent comparisons of noise levels in the previous study (Blackwell and Greene 2002) and sound levels measured in the current study. Monitoring of noise should continue in Cook Inlet to track changes in noise levels in the inlet over time and to determine if these changes are correlated with changes in the CIB population.

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Table 2.1 Hearing Capabilities of Species Residing in Cook Inlet (NPD: no published data, **California sea lion)

Group	Species present in Cook Inlet	Hearing range	Sound production	References
Odontocetes				
	Killer whale	500 Hz – 120 kHz	500 Hz – 25 kHz	Hall and Johnson 1972; Moore *et al.* 1988; Bain *et al.* 1993
	Beluga whale	40 Hz – 150 kHz	250 Hz – 20 kHz	Johnson *et al.* 1989; Au 1993; Sjare and Smith 1986a, 1986b
	Harbor porpoise	1 – 110 kHz	2 – 150 kHz	Andersen 1970; Busnel and Dziedzic 1966; Schevill *et al.* 1969; Akamatsu *et al.* 1994
	Dall's porpoise	NPD, assumed similar to harbor porpoise	40 Hz – 149 kHz	Evans 1973; Evans and Awbrey 1984
Mysticetes				
	Gray whale	NPD	20 Hz – 2 kHz	Swartz and Cummings 1978; Moore and Ljungblad 1984
	Minke whale	NPD	60 Hz – 20 kHz	Schevill and Watkins 1972; Winn and Perkins 1976
	Humpback whale	NPD	30 Hz – 8 kHz	Payne and Payne 1985
Pinnipeds				
	Harbor seal	100 Hz – 60 kHz	100 Hz – 150 kHz	Kastak and Schusterman 1995; Mohl 1968; Hanggi and Schusterman 1992, 1994; Noseworthy *et*

Table 2.1 continued…

				al. 1989
	Steller sea lion	100 Hz – 40 kHz**	500 Hz – 8 kHz**	Schusterman *et al.* 1967; Schusterman at al. 1972; Kastak and Schusterman 1995; Schusterman 1981
Teleosts, hearing generalists		100 – 400 Hz		Popper 2003
	Pacific salmon	20 – 600 Hz		Hawkins and Johnstone 1978; Knudsen *et al.* 1992, 1994
	Pacific herring	30 – 1200 Hz	1.7 – 22 kHz	Enger 1967; Wilson *et al.* 2004
	Pacific cod	60 – 310 Hz	50 – 64 Hz	Chapman and Hawkins 1973; Brawn 1961
	Sablefish	NPD		
	Lingcod	NPD		
	Rockfish	NPD	80 – 100 Hz	Stocker 2002; Miyagawa and Takemura 1986
	Halibut	NPD		
	Walleye Pollock	NPD		
Crustaceans	Crabs (tanner, Dungeness)	NPD		
	Shrimp/prawns (pink, sidestripe, northern, coonstripe, spot)	NPD		
Cephalopods	Octopus	50 – 150 Hz		Kaifu *et al.* 2007

Table 2.2 Hydrophone Information

Information for each of the three hydrophone deployments utilized in this study including hydrophone location, season of study, latitude and longitude, hydrophone depth, and deployment and retrieval dates. The study duration is the number of days within the deployment that fell within our study definitions of summer (July-September) and winter (December-February).

Location	**Eagle Bay**	**Trading Bay**	**Trading Bay**
Season	Summer	Summer	Winter
Latitude	61 N 16.668	60 N 53.482	60 N 53.433
Longitude	149 W 44.206	151 W 38.232	151 W 38.257
Depth	27 ft.	48 ft.	48 ft.
Deployment date	7/7/09	6/30/09	12/9/09
Retrieval date	8/16/09	11/8/09	5/2/10
Study Days	7/7 – 8/16	7/1 – 9/30	12/9 – 2/1

Table 2.3 Sound Spectra Summary

The mean (SD), median, minimum, and maximum sound pressure level (dB re 1 μPa) are shown within each one-third octave band as specified by the central band frequency (Hz) for Eagle Bay summer (EBS), Trading Bay summer (TBS) and Trading Bay winter (TBW).

	EBS				TBS				TBW			
Central Frequency (Hz)	Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max
100	74 (4)	72	70	109	81 (7)	79	71	109	82 (8)	81	71	106
125	60 (4)	58	56	94	68 (8)	65	57	98	70 (9)	68	57	93
160	48 (5)	46	43	80	55 (10)	51	43	89	58 (10)	56	44	83
200	46 (4)	44	42	73	52 (10)	48	42	86	55 (10)	52	43	77
250	47 (4)	46	43	77	54 (9)	51	43	84	56 (8)	54	44	76
315	49 (4)	47	44	77	58 (7)	57	45	83	59 (6)	58	46	75
400	50 (4)	49	45	78	59 (6)	58	47	81	59 (5)	58	47	74
500	50 (3)	49	47	78	60 (6)	60	48	80	60 (4)	59	50	74
630	51 (3)	50	48	80	62 (5)	62	49	83	61 (4)	61	50	76
800	52 (2)	51	49	81	64 (5)	63	50	85	61 (4)	61	52	82
1000	53 (2)	52	51	84	65 (5)	64	52	87	62 (4)	61	54	79
1250	56 (2)	55	54	87	66 (5)	66	56	90	63 (3)	63	56	80
1600	56 (2)	55	54	89	67 (4)	67	56	92	64 (3)	63	57	83

Table 2.3 continued…

2000	56 (2)	55	54	92	67 (5)	67
2500	56 (3)	56	55	94	67 (5)	67
3150	57 (2)	57	56	94	64 (4)	64
4000	58 (2)	57	57	92	63 (4)	62
5000	58 (2)	57	57	92	62 (3)	61
6300	57 (2)	57	56	92	61 (3)	60
8000	55 (3)	55	54	90	59 (3)	58

56	93	65 (4)	64	56	85
56	94	61 (3)	60	56	79
56	91	60 (2)	59	56	78
57	86	59 (2)	59	57	76
57	88	59 (1)	59	57	75
57	89	59 (1)	58	57	72
55	85	56 (1)	55	55	68

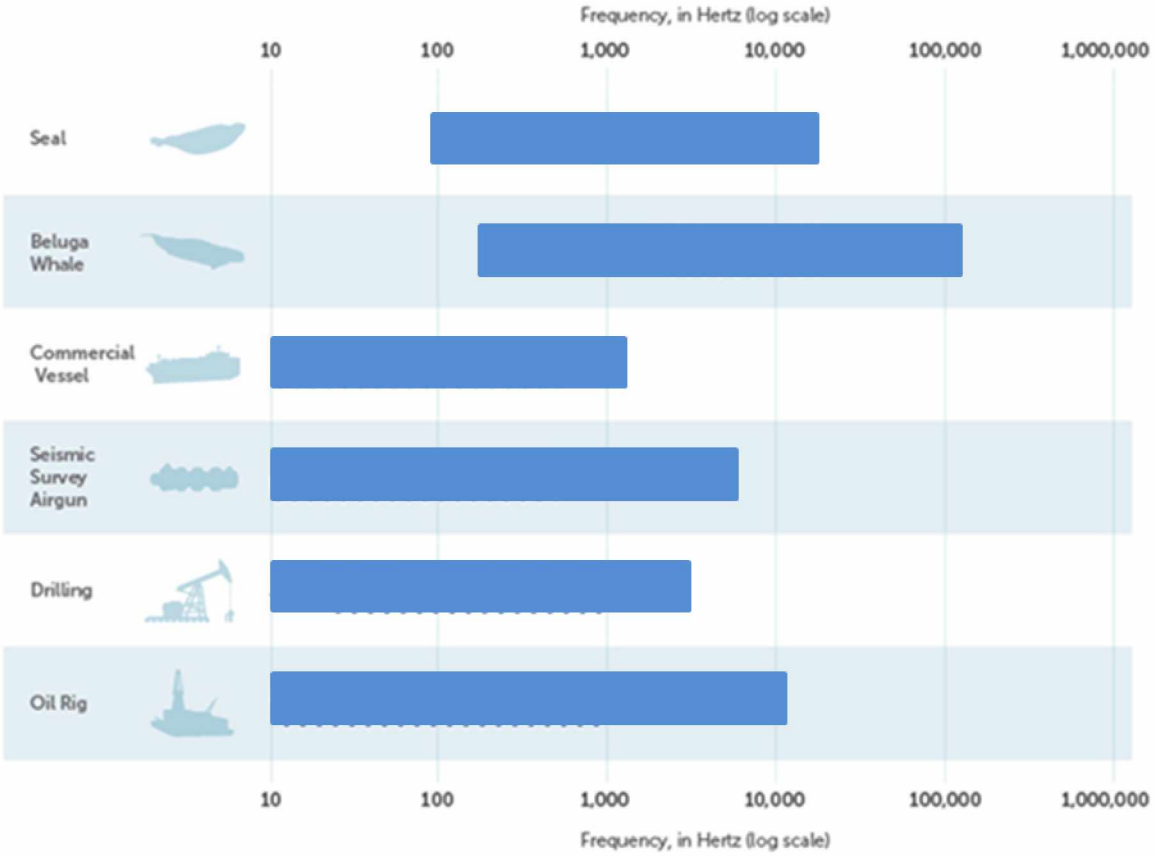

Figure 2.1 Marine Mammal Hearing and Anthropogenic Activities. Frequency overlap between marine mammal hearing and noise produced by anthropogenic activities. Shown are two marine mammals that inhabit Cook Inlet, harbor seals and beluga whales, and four anthropogenic activities, commercial vessel traffic, seismic air gun surveys, drilling, and operating oil rigs. Frequency (Hz) is shown on the horizontal axis. Hearing frequencies and frequencies of emitted sounds are represented by the horizontal bars next to each marine mammal and anthropogenic activity.

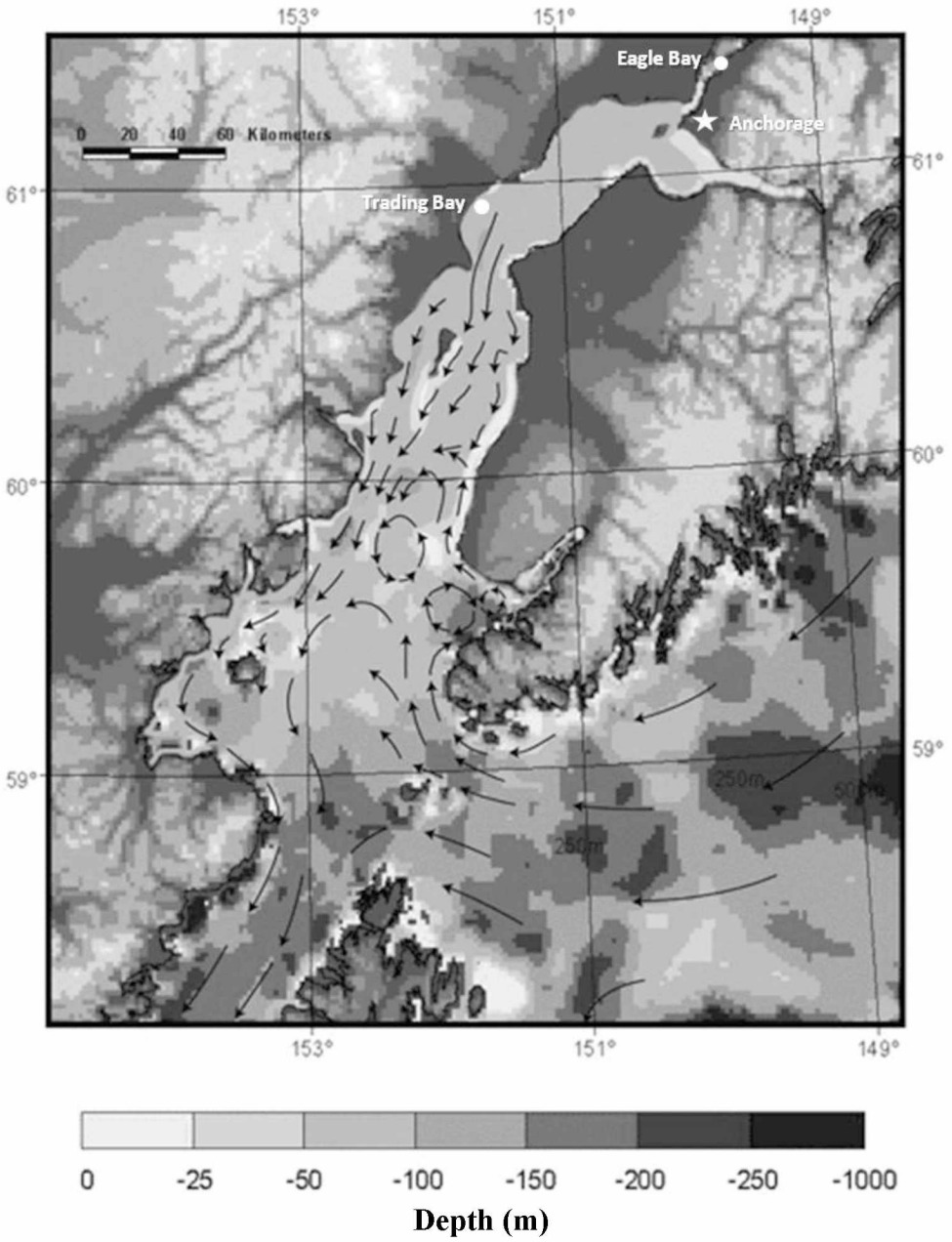

Figure 2.2 Bathymetry and Currents in Cook Inlet, Alaska. Hydrophone mooring locations (circles) are shown in Eagle Bay and Trading Bay. (Source: USGS).

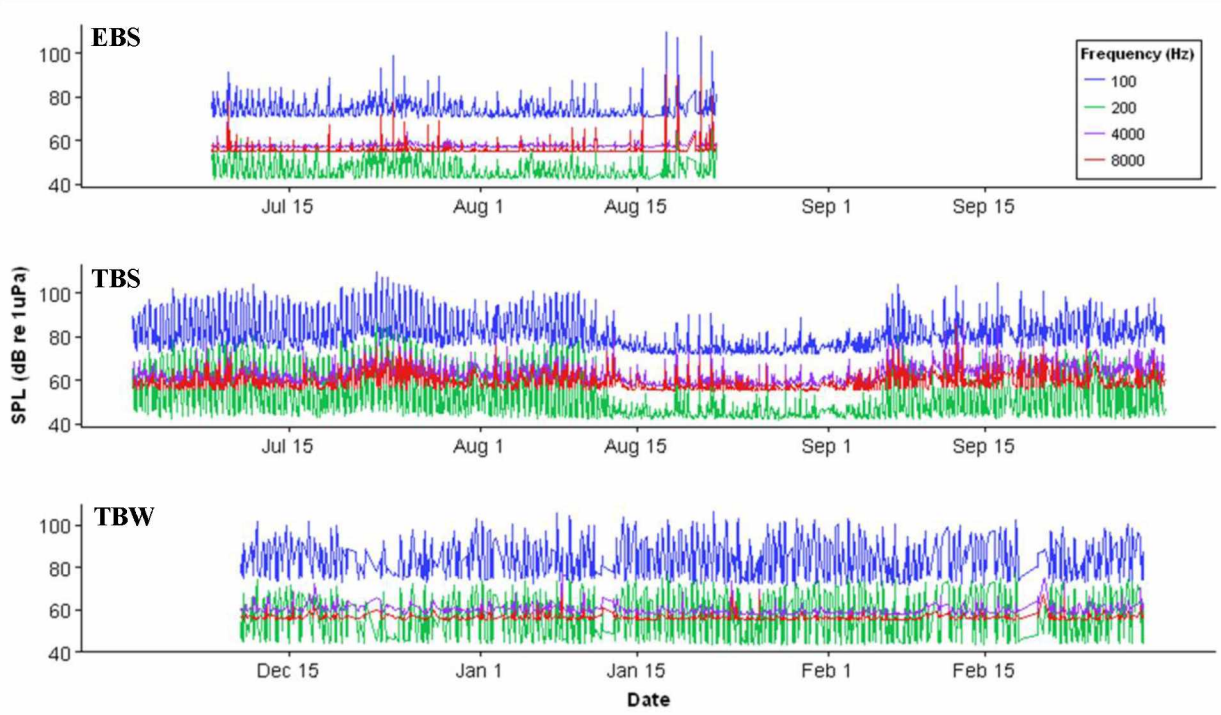

Figure 2.3 Sound Levels over Time. Time series of root mean square (RMS) sound pressure level (SPL) measurements in Eagle Bay summer (EBS), Trading Bay summer (TBS), and Trading Bay winter (TBW). RMS SPLs are denoted on the vertical axis and date on the horizontal axis. The highest RMS SPLs were in the 100 Hz band (blue line), the lowest frequency band in the study. The lowest RMS SPLs were in the 200 Hz band (green line). The 8000 Hz band (red line) was the highest frequency band in the study. The 4000 Hz band (purple line) is shown to represent the mid-frequencies. When these frequencies overlap, there is the potential for masking.

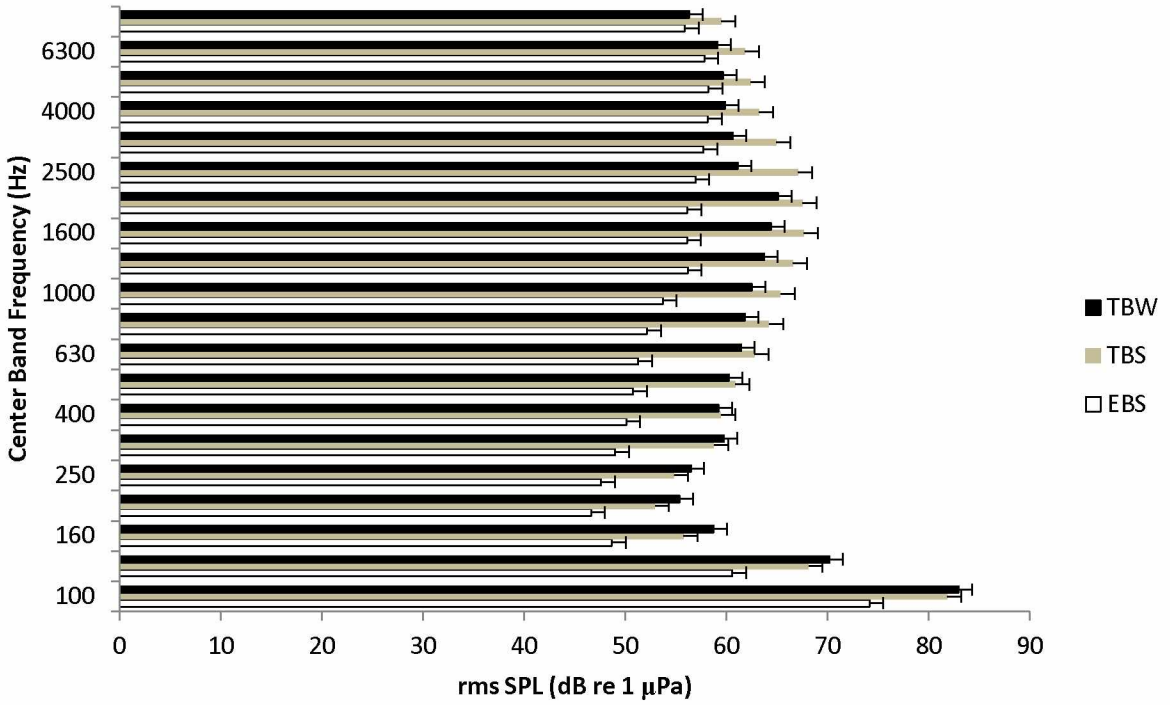

Figure 2.4 Mean Sound Pressure Levels. Mean root mean square (RMS) sound pressure level (SPL) measurements in Cook Inlet across one-third octave bands, denoted by their center band frequency (Hz). Eagle Bay summer (EBS) is represented in white, Trading Bay summer (TBS) in gray, and Trading Bay winter (TBW) in black. Error bars show the standard error.

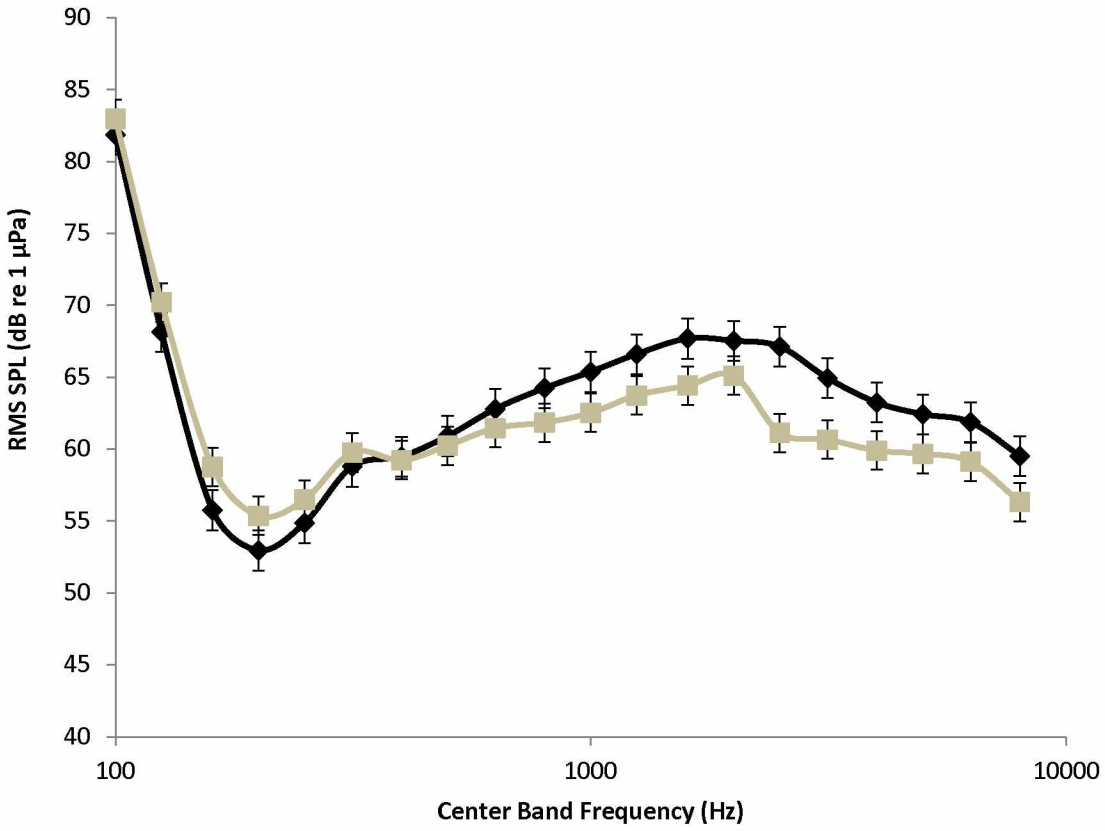

Figure 2.5 Seasonal Comparison of Sound Levels. Seasonal comparison of mean root mean square (RMS) sound pressure level (SPL) measurements across one-third octave bands, denoted by their center band frequency (Hz), in summer (black diamonds) and winter (gray squares). Error bars represent standard error.

Chapter 3 : Local Ecological Knowledge of Beluga Disturbance in Cook Inlet, Alaska[1]

Abstract

Cook Inlet beluga whales are a geographically and genetically isolated population residing in Cook Inlet, Alaska year round. The population declined by approximately 50% between 1994 and 1998 and was listed as endangered under the Endangered Species Act in 2008. The original decline was attributed to overharvest; however, the population has failed to rebound despite the virtual absence of harvest since 1998. This suggests that other factors, such as underwater noise, may be limiting the population's recovery. This study sought to document local ecological knowledge (LEK), knowledge gained through observation of the environment, to document changes in noise levels in Cook Inlet over time and Cook Inlet belugas' reactions to noise disturbance. Participants were sought from a variety of user groups including commercial, sport, and subsistence fishermen; non-fishing commercial users; researchers; and resource managers. Questionnaires were electronically distributed to participants and a subset of questionnaire respondents were selected for semi-directive interviews. A majority of questionnaire respondents felt that noise levels in Cook Inlet have increased over time due to a variety of activities including increased boat traffic, oil and gas development, coastal development, and air traffic. Most participants observed Cook Inlet belugas exhibit avoidance reactions to noise such as diving or leaving an area. Boats, planes, explosions, pile driving, construction, and car noise were all reported to cause changes in beluga behavior. Respondents also reported a change in seasonal distribution of Cook Inlet belugas which they attributed to the increase in participation in sport fishing in the Kenai River area. The results of this study show that noise is perceived to

[1]Blevins, R., S. Atkinson, and M. Murray. Local ecological knowledge of disturbance of beluga whales, *Delphinapterus leucas*, in Cook Inlet, Alaska. Prepared for submission to *Marine Fisheries Review*.

alter beluga behavior and possibly beluga distribution in Cook Inlet. A greater understanding of the bioenergetic costs of avoidance reactions is needed to determine how these reactions affect individual beluga whales and the Cook Inlet beluga population as a whole.

Introduction

Ethnoecology, the study of how people view their environment and how they interact with the surrounding ecosystems, involves local people and stakeholders in research. Local and traditional knowledge studies are specific types of ethnoecology studies that rely on a person's or culture's knowledge of an environment and the species within it. Local ecological knowledge (LEK) is knowledge gained through observation of a person's surroundings (Gilchrist et al., 2005). Longtime residents in a region often possess LEK obtained through their experiences. Traditional ecological knowledge (TEK) is "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission" (Moller et al., 2004) and has a holistic viewpoint including humans as part of the ecosystem (Huntington, 1998).

Local ecological knowledge and TEK studies have certain drawbacks. A major criticism of such studies is that it can be dismissed as anecdotal (Mauro and Hardison, 2000) or may be considered unreliable because it is not subjected to the rigorous review processes utilized in Western science (Lewis et al., 2009). Also, TEK and LEK are often spatially limited (Lewis et al., 2009). Despite the limitations, there are benefits of using LEK or TEK. Traditional ecological knowledge spans large time scales and can be used to establish baselines (Mauro and Hardison, 2000) filling gaps in existing research (Carter and Nielsen, 2011). Traditional knowledge can be particularly helpful for the study of marine mammals as its long-term scope provides the information necessary for the conservation of long-lived, slowly-reproducing species (Moller et al., 2004) such as whales. While LEK often spans shorter time periods than TEK, it has the potential to cover larger time scales than many scientific studies. Traditional ecological knowledge and LEK are sometimes criticized for emphasizing unusual events as those are the most memorable (Krupnik and Jolly, 2002). However, the documentation of these

unusual events can be a benefit as scientific studies often miss short term anomalies or unusual events. Local ecological knowledge and TEK provide opportunities to broaden research and improve ecological impact assessments (Huntington, 2000a). It has been recognized that the integration of scientific knowledge and LEK, termed co-science, may improve current management strategies and further beluga recovery (Harwood et al., 2002). Such integrated management (co-management) of marine resources has proven effective in many locations (Freeman et al., 1998).

This study utilized LEK to document Cook Inlet belugas' reactions to noise. There are several user groups in Cook Inlet with extensive on-the-water experience including commercial fishermen, other commercial users, researchers, and non-commercial users. Previous TEK studies in Cook Inlet have focused on a variety of topics (Huntington, 2000b; Carter and Nielson, 2011), including beluga distribution in Cook Inlet, ranging from the small-scale, daily movements of beluga whales (Huntington, 2000b) to their large-scale, seasonal distribution patterns (CIMMC, 1996; Huntington, 2000b). The feeding habits and diet of Cook Inlet belugas (CIBs) have also been studied through TEK (Huntington, 2000b). Additionally, TEK has also provided other information such as beluga behavior and life history (Stanek, 1994; Council, 1996; Huntington, 2000b). No published TEK studies have sought information on the perceived effect of noise on the Cook Inlet beluga (CIB) population. However, reactions to noise were mentioned in a previous study suggesting the need for further study of the issue (Carter and Nielson, 2011).

Located in south-central Alaska, Cook Inlet is a semi-enclosed tidal estuary (Figure 3.1) approximately 370 km long and 32 km wide. The inlet is fairly shallow, less than 60 m deep in most places. Several major rivers flow into the upper inlet depositing a large amount of glacial

silt. Cook Inlet experiences the largest tidal regimes in the United States with a typical range of 9 meters per day (Mulherin et al., 2001). Anchorage, the largest city and port in Alaska, is located on Cook Inlet, and the Cook Inlet watershed is home to 400000 residents, approximately 2/3 of Alaska's population (Cook Inlet Keeper, 2015, see www.inletkeeper.org/about/watershed). Cook Inlet is home to one of the five management stocks of beluga whales, *Delphinapterus leucas*, in Alaska. The CIB population, the smallest stock, is isolated both genetically and spatially (O'Corry-Crowe et al., 2003) remaining in Cook Inlet year-round (Hobbs et al., 2005). The other management stocks are found in Bristol Bay, the eastern Bering Sea, the eastern Chukchi Sea, and the Beaufort Sea.

The CIB population was estimated to have declined by almost fifty percent between 1994 and 1998 (Hobbs et al., 2000). This sharp decline was ascribed to overharvest by subsistence hunters and led to the voluntary suspension of the hunt in 1999 (Moore and DeMaster, 2000). The CIB habitat range began to contract concurrently with this population decline (Rugh et al., 2000). The historic CIB range covered most of Cook Inlet and may have included occasional trips into the Gulf of Alaska (Laidre et al., 2000). Since the population decline, belugas have seldom been sighted south of the Forelands, located mid-inlet (Figure 3.1) (Hobbs et al., 2005). This northward contraction in their range has confined belugas to the areas of Cook Inlet with the highest human population densities, including Anchorage (Rugh et al., 2010), increasing the potential risks associated with anthropogenic interactions. Despite the removal of hunting mortality, the CIB population has shown no sign of recovery (Hobbs et al., 2008). The population exhibited an average decline of 1.1% per year between 2001 and 2011 (Allen and Angliss, 2013). Due to this continued decline following the suspension of the subsistence harvest, the population was listed as endangered under the Endangered Species Act in 2008 (73

FR 62919), and critical habitat was designated in 2011 (76 FR 20180). The lack of recovery despite the virtual absence of subsistence harvest suggests there are likely additional factors hindering the CIB recovery. Several such factors have been proposed including declining prey availability, increased predation, contaminants, disease, climate change, catastrophic events, habitat loss, unauthorized take, and underwater noise pollution (NMFS, 2015), but there are currently few data to support any of these factors.

Concern has grown over the potential impacts of underwater noise pollution on many marine mammal populations. A variety of human activities generate noise in the marine environment including commercial shipping, boating, oil and gas activities, marine and coastal construction, military activities, and scientific research utilizing active hydroacoustics. Underwater anthropogenic noise has the potential to mask signals such as echolocation clicks, calls from conspecifics, prey sounds, and predator calls (Richardson et al., 1995). Masking has the potential to limit population growth and interfere with the recovery of an endangered population (Tyack, 2009) such as CIBs. "While noninjurious consequences [of anthropogenic sound], such as beluga avoiding an area of boat traffic, may seem unimportant, displacement from feeding or calving habitats could be very harmful to the recovery of this population" (Hobbs et al., 2006). "If an anthropogenic signal stimulates a disturbance response, then this response may cost the animal in terms of energy and lost opportunities. Sound may also trigger stress responses, which involve other physiological costs. Some sound exposures may be loud enough to make it more difficult for an animal to perform its regular functions" (Tyack, 2008). Some marine mammal species can compensate for the effects of masking by changing the frequency or source level of their acoustic emissions, repeating their signals, or altering the timing of their signals to increase the chances the call will be detected by conspecifics (Lesage et al., 1999; Foote et al., 2004;

Morisaka et al., 2005; Holt et al., 2009). However, these techniques may have metabolic costs (Jensen et al., 2009). Marine mammal reactions to noise disturbance are highly variable and context-specific, affected by both behavioral state and group composition among other factors (Richardson et al., 1995). Noise may lead to avoidance reactions, no visible reaction, or, in some cases, attraction (Richardson et al., 1995). Behavioral reactions to noise may displace animals from preferred habitat or affect their energy budget (Lusseau, 2003; Bejder, 2005; Lusseau et al., 2009). Noise can also cause changes in acoustic behavior of marine mammals. Belugas are capable of altering the frequency and duration of their calls in response to noise (Lesage et al., 1999). The issue of underwater noise will likely increase in the future due to increased levels of human activity in the marine environment. Increased ambient noise levels may be exacerbated in some areas as climate change leads to increasing water temperatures and ocean acidification (Sehgal et al., 2010). The expected increase in underwater ambient noise levels and the declining beluga population in Cook Inlet make it important to examine how belugas in Cook Inlet react to noise.

The present study sought to understand how stakeholders in Cook Inlet perceive noise affects CIBs. The objectives were to: (1) record individuals' observations of responses by belugas to noise in Cook Inlet; (2) document stakeholders' perception about how noise levels may have changed in Cook Inlet over time; and (3) record how the potential issue of noise is perceived by Cook Inlet users.

Methods

Potential participants were identified by contacting scientists and managers working in Cook Inlet as well as commercial fishing groups, tug boat companies, and non-commercial companies. We sought participants that would have local knowledge based on several years of experience in Cook Inlet, ideally with observations of belugas within the inlet. We targeted a

variety of user groups including commercial fisherman, sport fisherman, subsistence fisherman, non-fishing commercial user, researcher, resource manager, Cook Inlet resident, government employee, or members of the CIB recovery team. Once potential participants were identified they were contacted via email or phone to introduce them to the research project and to determine whether they were interested in participating. Electronic questionnaires were distributed to those who self-selected to participate. Questionnaires were selected for the first phase of the project as they are useful when seeking information on specific topics, and they allow participants to introduce additional topics of interest beyond the researcher's original scope (Huntington, 2000a). We sought a maximum of 30 questionnaire participants.

Within the questionnaire, participants were asked questions to gauge their experience in Cook Inlet; to catalog their observations and knowledge of the CIB population; to document CIBs' reactions to noise; and to determine their perspective on changes in noise levels in Cook Inlet and the role of noise as a potential issue for the CIB population. First, the questionnaire covered the demographic information of the participant's age, gender, and town of residence. The participants were asked to self-identify with one or more of the following user groups: commercial fishermen in Cook Inlet, sport fisherman in Cook Inlet, subsistence fisherman in Cook Inlet, non-fishing commercial user (i.e. tug boat captain, oil and gas employee, etc.), researcher, resource manager, Cook Inlet resident, government employee, member of the CIB recovery team, or an 'other' category which allowed the participant to specify their use of Cook Inlet. Then participants were asked how many years on-the-water experience they had in Cook Inlet and whether or not they had observed CIBs. In the next section, participants could self-identify as an Alaska Native to answer questions specific to that user group. The following section of questions addressed observed changes in the CIB population and potential factors

affecting the population. The final section focused on the issue of noise in Cook Inlet, how noise levels may have changed, and observations of CIBs' responses to noise disturbance. For a full list of questions, see Table 3.1.

Questionnaire answers were analyzed through text analysis to identify the most common answers, to note unique responses, and to evaluate whether responses varied based on user group. Observed beluga reactions to noise were cataloged. The results of the questionnaire were used to shape the topics and questions for subsequent one-on-one interviews and to help identify appropriate interviewees based on experience.

Based on their experience and observations, a subsample of questionnaire participants was asked to participate in phone interviews. Self-selected participants were interviewed using the semi-directed interview technique (Huntington, 2000a) in which the interviewer guides the discussion but allows the participant to define the direction and scope of the conversation, an ideal technique for documenting LEK and TEK (Huntington, 1998). This open-ended interview format allows for greater coverage of the topic than may be anticipated by the interviewer (Huntington, 1998). The object of the interviews was to cover certain topics from the questionnaire in more detail and to explore new topics that arose in the questionnaire answers. Based on the questionnaire responses, the following topics were selected for discussion during the interviews: variation in belugas' response to similar noise sources, beluga attraction to sounds, differences in beluga reactions to noise, desensitization to noise, the most significant source of noise in Cook Inlet, the biggest threat to the CIB population, beluga strandings in Cook Inlet, the sport fishery in the inlet, indirect effects of noise on CIBs, and observations of other beluga populations. The interviews were recorded using an Olympus VN-7200 Digital Voice Recorder and then transcribed and evaluated.

Results

Twenty-three Cook Inlet users completed questionnaires. All user group categories were represented across the 23 respondents (Table 3.2). In the 'other' category, respondents reported working as a marine surveyor or being involved with the Cook Inletkeeper or the Cook Inlet Regional Citizens Advisory Council. Fourteen participants were males and 9 were females. Reported ages ranged from 31 to 62 (Figure 3.2). On-the-water experience ranged from 5 to 48 years with 13 respondents having 20 years or more of on-the-water experience, suggesting they likely observed changes in the Cook Inlet environment during the CIB population decline (Figure 3.3). While one respondent self-identified as a subsistence fishermen, no respondents reported being Alaska Native.

Fourteen respondents reported that the CIB population had declined during their time on the water. Seven reported seeing no change in the population, and two did not answer. Among those participants who had witnessed a decline, many attributed the decline to overharvest of CIBs reported in the scientific literature. Respondents also cited changes in prey availability, oil and gas development, an increase in killer whale abundance leading increased predation, pollution, and habitat loss. Some respondents believed the cause of the decline remains unknown. Of those who had seen a decline in the CIB population, only 4 reported observing any recovery. Three reported seeing greater numbers of belugas over greater ranges, and one reported seeing more young whales.

A majority of questionnaire participants, 13 out of 23, reported that noise levels in Cook Inlet have changed. A variety of sources were cited as the cause of the increase in noise levels (Table 3.3). Only four respondents answered that noise levels have not changed, and six chose not to answer the question.

Twelve respondents reported observing belugas respond to anthropogenic noise. Questionnaire respondents reported observations of beluga reactions to a variety of noise sources including boats, aircraft, explosions, pile driving, construction noise, cars, and human voices (Table 3.4). Reported responses were generally avoidance reactions such as diving or vacating the area, changing surfacing behavior by surfacing less frequently or for shorter periods, or ceasing acoustic communication (Table 3.4). There were a few cases of beluga approach (Table 3.4). One respondent reported young belugas approaching the transponder of a depth finder while the boat engines were off. An anchor chain hitting a boat deck caused a beluga group to stop surfacing and dive. The adults left the area while the younger belugas approached the boat. Only one natural noise source, calls from conspecifics, was reported to elicit a reaction from CIBs however the reaction was not described.

The perceived costs of CIBs' reactions to noise varied among questionnaire participants. Reactions that involved disruptions in movement or displacement were thought to potentially place belugas in unsuitable or less suitable habitats. One participant responded that belugas may move into shallower water to avoid a noise source placing them at greater risk of stranding. Other respondents felt that belugas evading noise sources may be prevented from utilizing important foraging areas thereby limiting their feeding opportunities. Another respondent felt that belugas' reactions to noise would affect their communication. A majority of reactions were noted as being short term. While these short term reactions were believed to have only small energetic costs, it was recognized by some respondents that repeated or prolonged disturbances could adversely impact individual belugas and may result in chronic stress.

A majority of questionnaire respondents, 16 out of 23, believe that noise affects CIBs in a variety of ways (Table 3.5). Three respondents did not believe noise affects CIBs, and 4 did not

answer. Fourteen out of 23 questionnaire respondents thought noise was a serious concern for the CIB population; five did not believe that it was a concern, and four chose not to answer the question. When asked, respondents offered a variety of potential measures to reduce the impact of noise on the CIB population (Table 3.5). While noise was generally recognized as a concern for the population, it was not considered to be the main factor limiting the recovery of CIBs. Respondents identified a variety of causes limiting the recovery of the population (Table 3.5), many listing multiple factors in their answer. Some respondents believed that there has not been sufficient time for the population to recover. Questionnaire participants also discussed the possibility that the population has dropped too low to be able to recover.

Questionnaire responses were evaluated for trends based on age, on the water experience, or stakeholder group. The only trend based on respondent's age that was identified was the four oldest respondents were the only participants that reported observing signs of recovery in the CIB population. There were no trends in questionnaire answers based on on-the water experience. Trends based on stakeholder group were difficult to evaluate as many respondents identified with multiple stakeholder groups. There was general consensus in responses across stakeholder groups for most questions with contradictory responses spread across stakeholder groups. There were two cases of a unanimous response within a stakeholder group. Among Cook Inlet residents, every respondent who answered the question reported that noise levels have increased in Cook Inlet. Every researcher who answered the question felt that noise was a concern for the CIB population. The only respondents who felt that noise does not affect CIBs and/or is not a concern for the population were sport fishermen or non-fishing commercial users. This response was not unanimous across these user groups and some of these participants were members of additional user groups. Interestingly, increases in levels of sport fishery

participation as a source of increased noise in the inlet or as a factor affecting CIBs were cited by both commercial and sport fishermen.

Three questionnaire respondents consented to participate in follow-up interviews. Their on-the-water experience ranged from seven to 40 years, and they represented commercial fishermen, researchers, Cook Inlet residents, and the CIB recovery team.

First, interviewees were asked about their observations of belugas around noise sources identified in questionnaire responses as eliciting a reaction by belugas. While cars were cited as eliciting a response in the questionnaire (Table 3.4), interview participants had not observed any reaction of belugas to car noise despite being in the proximity of belugas when cars were present. One interviewee had observed belugas during aircraft overflight but not seen any reaction though aircraft noise was reported as a disturbance in the questionnaire (Table 3.4). One interviewee described changes in beluga surface behavior in the presence of boats. The interviewee observed belugas diving for longer periods and surfacing for shorter periods. The belugas also exhibited a cryptic surfacing behavior known as snorkeling where most of the body remains submerged when they surface to breathe. This response in the presence of boats was attributed to the history of beluga hunting in Cook Inlet.

Interviewees were also asked about beluga attraction to sound. One participant reported a positive response or attraction to female laughter from onboard a boat and to sliding a case across the bottom of a boat. The participant also reported beluga attraction to a site where gravel was being dumped into the inlet. It was not clear to the interviewee whether belugas were attracted to the noise itself or to potential prey being disturbed from the sea floor. The same interviewee has witnessed belugas approach a boat floating with the engines off suggesting that belugas were attracted to the boat presence itself rather than the noise. The other interviewees

had not witnessed beluga attraction in Cook Inlet but had observed beluga attraction in other locations. One participant had seen belugas approach boats in the St. Lawrence Estuary. The other interviewee has observed beluga attraction to propellers during capture though this attraction was attributed to the choppy water rather than the noise of the propeller itself. This participant also reported an aggressive approach from a beluga while aboard a boat in Svalbard, Norway. In each of these cases except for the aggressive approach, it was young, grey whales that approached. Interviewees observed that older whales tended to be more wary or at least less curious than the juveniles. One hypothesized that perhaps the older whales had experience with the sound before and that the younger whales approach to investigate the novelty.

While interview participants had not witnessed habituation or desensitization, they had observed belugas in areas where noise-producing activities occur. One interview participant reported continued beluga presence in an area of intense construction noise and the continued utilization of Eagle Bay by mothers and calves despite military activity. Another interviewee witnessed belugas travel within close proximity of operating oil rigs. Interviewees thought belugas may habituate or become desensitized to constant, low level noises while finding sudden or intense noises disturbing.

When asked about the most significant noise source in Cook Inlet, interviewees' answers varied. One participant felt it was not one specific noise source but the combination of noise sources that is significant and that a better understanding of how the effect of chronic, low-level noise compares to that of intermittent, intense noise is needed. Of particular concern could be an intense, novel noise source introduced in a habitat utilized by sensitive members of the population such as mothers and calves. Another interviewee felt that the most significant noise sources in the inlet are sudden noises such as explosions, pile driving, or seismic work. This

interviewee felt one of the biggest threats to the population was the small population size which could inhibit recovery and make CIBs more prone to social disturbance or catastrophic events such as disease outbreak.

Questionnaire respondents were concerned about stranding events, and this topic was explored in interviews. One participant admitted to being curious about possible connections between loud, intense events such as explosions and seismic exploration and strandings that came shortly after said events. However this participant acknowledged that similar loud events have not been followed by strandings, and without baseline information it cannot be determined whether there is a correlation between these events or if they are merely suspicious coincidences. Another participant was concerned about the potentially disastrous consequences to the CIB population given previous incidences of mass strandings in the inlet and their unpredictability.

During interviews the increase in the sport fishery, another questionnaire topic, was also discussed. One participant had spoken to fishermen around Kenai who observed a reduction in beluga presence in the area which they attributed to fishing activity in the region. This participant also reported belugas were sighted in the Kenai area only at the beginning and end of the fishing season rather than during the peak fish run when belugas would be expected to be present to forage. However, the avoidance of the area by belugas may not be due to the noise itself but to the prevention of boat strikes and net entanglements. This interviewee reported witnessing boats drive over groups of belugas in the Kenai River and a beluga calf become entangled in a net. Another interviewee confirmed that belugas no longer travel up the Kenai in general despite utilizing the river historically. This participant also cited the intense human activity in the river as the reason for beluga exclusion. However this participant felt the greater concern is overharvest, and it is more important that the fishery is managed to allow enough prey

for belugas. This interviewee was concerned about hooligan or eulachon, *Thaleichthys pacificus*, runs in Cook Inlet. Hooligan is an important spring food source for CIBs, and human harvest of the species has been increasing but minimally regulated. A better understanding is needed of the biology of this species and the biomass available in Cook Inlet.

The final topic that arose in questionnaires, and was discussed in interviews, was the potential for indirect effects of noise on the CIB population. Some questionnaire respondents were more concerned how noise could affect fish and how that in turn would affect belugas rather than how noise directly affected the belugas themselves. When interviewees were asked about this issue, they responded that it was a topic that warranted further study to better understand the potential effects of noise on fish in Cook Inlet. This topic was deemed especially relevant by one interviewee given the upcoming expansion of the Seward Highway.

Discussion

Reactions of cetaceans to noise disturbance are highly variable. Beluga reactions to disturbance are often affected by the activity in which the whales are engaged, the age of the whales, the pod composition, and the habitat they are currently occupying (Bel'kovich, 1960; Kleinenberg et al., 1964; Blane, 1990). Traveling and feeding belugas are less likely to react to boat presence than belugas engaged in other behaviors (Blane, 1990; Blane and Jaakson, 1994). Purposeful harassment has been unsuccessful at displacing feeding belugas (Fish and Vania, 1971), and belugas have been observed feeding among large numbers of fishing boats in Bristol Bay, Alaska (Frost et al., 1984). Feeding belugas are also resistant to disturbance by aircraft (Bel'kovich, 1960; Kleinenberg et al., 1964). Young beluga whales are less likely to react to disturbances than older whales (Blane, 1990; Blane and Jaakson, 1994); lone whales and whales in small pods are more likely to be disturbed than whales in larger groups (Bel'kovich,1960; Kleinenberg et al., 1964).

Previously documented reactions of belugas to boats range from little or no reaction to extreme disturbance. Reactions of belugas to boat disturbance include leaving the area, changes in traveling direction, and changes in behavior (Richardson et al., 1995). Belugas in Cook Inlet exhibited similar behavioral responses according to participants in the present study (Table 3.4). Previously reported disturbance reactions were affected by a number of factors including the belugas' activity, the population's previous experience with disturbance, physical characteristics of the belugas' habitat, and boat size, speed, and direction of travel (Richardson et al., 1995). Beluga whales tend to be more responsive to small boats than large vessels; belugas in several areas including the St. Lawrence River, Cook Inlet, and the Beaufort Sea have shown little reaction to large boats traveling in a consistent direction (Fraker, 1977b; Macfarlane, 1981; Sergeant, 1981; Burns and Seaman, 1985; Pippard, 1985; Sergeant, 1986). Approach by small boats often causes belugas to flee, particularly if the boats are moving quickly or erratically (Fraker, 1977a; 1978), and belugas are more responsive to outboard motors than other small vessels (Stewart et al., 1982). The reactions of belugas to boats reported in the questionnaire were to small vessels. One respondent reported minimal reaction to tug boat traffic suggesting that, as in other regions such as the St. Lawrence Estuary and the Beaufort Sea (Macfarlane, 1981; Burns and Seaman, 1985), Cook Inlet belugas seem less responsive to large boats than smaller vessels. The number of boats can also affect beluga reactions. Belugas in the St. Lawrence Estuary displayed strong disturbance reactions when approached by multiple boats traveling at speeds above idle, particularly if approached from different directions (Blane, 1990; Blane and Jaakson, 1994). While there were no reported observations of approach by multiple boats in Cook Inlet, given the similarity of responses to other disturbances a comparable response to other beluga populations could be expected. Questionnaire respondents reported

CIBs avoiding boats even when they were not approaching the whales or when the motors were idling or turned off. This wariness of small boats could be partly attributed to CIBs' previous exposure to subsistence hunting which was conducted from small boats. Many beluga disturbance reactions, including those observed in Cook Inlet by participants in this study, were short lived, lasting only a few hours. However, disturbance can have more long-lasting effects. There have been cases of beluga displacement from an area for multiple days following ice breaking activity in the Arctic (Finley et al., 1990). Repeated disturbance had been shown to lead to changes in local distribution of beluga populations (Fraker, 1980; Brodie, 1981a; Brodie, 1981b; Reeves and Mitchell ,1981; Seaman and Burns, 1981; Sergeant, 1981; Finley, 1982; Finley et al., 1982; Burns and Seaman, 1985; Caron and Smith, 1990). In the St. Lawrence Estuary, increased boat activity in an area over multiple years led to a decline in beluga abundance in the region (Caron and Sergeant, 1988). In Cook Inlet, it was reported by participants in the present study that beluga abundance in the Kenai River area has changed as a result of increased human activity in the area due to the growth of the salmon sport fishery in the region.

Belugas generally exhibit avoidance behavior when disturbed by aircraft, often diving or vacating the area (Fraker, 1978; Fraker and Fraker, 1979; Finley, 1982; Finley et al., 1982; Gales, 1982; Caron and Smith, 1990). The reaction is often affected by the altitude of the aircraft. In one example from Russia, belugas did not react to planes flying at 500 m altitude but when aircraft flew over at 150 – 200 m altitude belugas began utilizing shorter surface times and longer dive intervals and some left the area (Bel'kovich, 1960; Kleinenburg et al., 1964). In waters off Alaska, some belugas showed no reaction to airplane overflights at altitudes as low as 100 – 200 m while other belugas dove suddenly or drastically changed their travel direction

during airplane overflights up to 460 m altitude (Richardson et al., 1991). Reactions seem similar for different types of aircraft. In the St. Lawrence overflights by both fighter jets and helicopters caused belugas to dive when overhead (Macfarlane, 1981; Sergeant and Hoek, 1988). Aside from causing belugas to dive or move out of an area, low-flying aircraft may prevent belugas from entering traditional habitat (Burns and Seaman, 1985). In Cook Inlet, belugas also appear to display avoidance responses to aircraft by leaving the area or changing their surface behavior (Table 3.4). Aircraft overflights may have even lead to a cessation in acoustic activity suggesting that plane disturbance may have the potential to affect beluga communication, according to a survey participant in the present study. However, there were no reports of habitat exclusion due to aircraft. Cook Inlet belugas continue to utilize Eagle Bay despite regular jet overflights. It may be, however, that this could be indicative of Eagle Bay serving as an important foraging and nursery habitat rather than a lack of disturbance to the belugas by the overflights.

As with vessels and aircraft, beluga reactions to other noise sources such as explosions, construction, and oil and gas activity vary. The use of small explosives to intentionally scare belugas away from salmon in Alaskan rivers has shown some limited efficacy (Fish and Vania, 1971; Frost et al., 1984). In our study, belugas were reported to be responsive to explosions causing belugas to dive, leave an area, or change their surfacing behavior (Table 3.4). Two interviewees reported extreme reactions to land-based explosions that caused belugas to dramatically alter their surfacing behavior or to quickly evacuate the area. This difference in the reported reactions to explosions may be attributed to the fact that the belugas in the previously reported case were engaged in foraging, an activity which may have made them less reactive to disturbance. Construction noise in Cook Inlet was reported to cause belugas to change their

travelling route and change their calling activity (Table 3.4). In the Arctic, construction equipment in use on an artificial island caused belugas to move further offshore, but they remained in the general area (Fraker, 1977a). Dredging noise was not reported to elicit a reaction in the present study, but dredging occurs in Cook Inlet and has been credited as one source of increasing noise levels in the inlet (Table 3.3). In other regions, dredging activity has been shown to block whale passage along the shoreline when barges are transiting through the area (Ford, 1977; Fraker, 1977a; Fraker, 1977b). However, when the barge was stationary and other support vessels were not present, belugas traveled within 400 m of the barge (Ford, 1977; Fraker, 1977a; Fraker, 1977b).

No reactions to oil and gas drilling or rig noise were reported in the present study. In fact, one interviewee reported observing belugas swimming in close proximity to operating oil rigs. The lack of reporting could be due to limitations in the participants' experience around rigs rather than a lack of beluga response to such noise. This type of noise exists in Cook Inlet and could affect CIBs. Beluga whales in the Arctic have been observed swimming within 100 – 150 m of artificial islands when drilling is in operation (Fraker, 1977a; Fraker, 1977b; Fraker and Fraker, 1989). In Canada's Mackenzie Estuary, belugas approached within 1 km of stationary drillships before changing their travel course (Norton Fraker and Fraker, 1982). Their reactions were much stronger when support boats were operating in the area (Norton Fraker and Fraker, 1982). In Alaskan waters, playback experiments with drilling noise showed that within 1.5 km of the noise source belugas increased their swimming speed and respiration rates and some changed direction when closer to the projector (Stewart et al., 1982; Stewart et al., 1983). However, some belugas did not react until within 100 m of the noise source and many swam within a short distance of the projector (Stewart et al., 1982; Stewart et al., 1983). In another

playback study, migrating belugas did not react to drilling noise until within 400 m of the projector (Richardson et al., 1990; Richardson et al., 1991). Some hesitated or altered their course slightly but passed within 50 to 200 m of the noise source (Richardson et al., 1990; Richardson et al., 1991). In a playback study with captive belugas, the whales showed a brief avoidance reaction during the first 30 seconds of playback but then swam within 1 m of the projector (Thomas et al., 1990). Catecholamine levels were measured in this captive experiment, and levels returned to normal within 8-40 minutes of playback ceasing suggesting that the physiological response to noise was short-lived (Thomas et al., 1990). Though there are currently no ongoing drilling projects in Cook Inlet, the noise emitted by operating rigs could influence CIB behavior though emitted noise levels would likely be lower and more constant than drilling. The number of seismic surveys utilized for oil and gas exploration has increased in Cook Inlet in recent years. The intense sound produced by these seismic surveys could also affect CIBs.

There is some evidence to suggest that belugas exhibit seasonal or long-term habituation. Belugas continue to return to certain summering areas year after year despite harassment due to heavy hunting pressure in these regions suggesting some degree of tolerance for boat disturbance (Fraker, 1980; Brodie, 1981a; Brodie, 1981b; Reeves and Mitchell, 1981; Seaman and Burns, 1981; Sergeant, 1981; Finley, 1982; Finley et al., 1982; Burns and Seaman, 1985; Caron and Smith, 1990). In the St. Lawrence Estuary beluga avoidance of approach by boats has become less common over time (Blane, 1990). In fact, whales approaching boats has become more common and is more frequent late in the summer season than early in the season (Blane, 1990). A similar pattern of approach has been observed in gray whales (Richardson et al., 1995). Belugas have also been reported to swim within 9 m of active oil rigs leading some oil workers

to believe that the belugas are tolerant of the steady noise produced by the rig (Gales, 1982). Habituation and noise tolerance was mentioned in the present study's questionnaire responses and was further explored in the interviews. No participants reported observing habituation or desensitization to noise, but several believed it occurs. While respondents had not seen direct evidence of habituation, they reported observing belugas near operating oil rigs and tug boats which they interpreted as tolerance. They also reported continued presence of belugas in noisy areas.

In the present study there were a few reported cases of belugas approaching a noise source. There have been some previously reported cases of beluga attraction to noise including attraction to boats in some instances (Blane, 1990; Blane and Jaakson, 1994). In Cook Inlet, flare booms used on oil rigs were observed to attract belugas (Gales, 1982). It was thought this could be due to the explosions attracting salmon rather than belugas being drawn to the noise itself (Gales, 1982). In the present study, the belugas attracted to noises were always the young, gray whales suggesting that young individuals may be more curious, particularly about novel noise sources.

There were disadvantages to using LEK to study underwater noise and its potential effects on beluga behavior. Despite its relatively large temporal scale, TEK and LEK is often spatially limited (Lewis et al., 2009). In some documented cases, belugas have reacted to disturbances up to 35 – 50 km, rapidly swimming out of the area when approached at this distance (LGL and Greeneridge, 1986; Cosens and Dueck, 1988; Finley et al., 1990). Monitoring of whales during vessel activity has shown icebreakers can cause belugas to travel 80 km away from their original location (Finley et al., 1990). Reactions at such a great distance would not likely be observed through LEK. Another potential issue with using LEK to study the

issue of underwater noise is that many noise sources reported to elicit a reaction are in-air noise sources. Transmission of noise from the air into the water is limited (Richardson et al., 1995) so the reported noise sources may have limited detectability by the belugas themselves. This is a problem inherent in utilizing human observers to study underwater noise. This study relies on the assumption that CIBs were reacting to the noise source identified by the participant rather than human presence itself or an unidentified stimulus. Also, bias can arise in the results due to nonrandom observation and lack of objectivity on the part of the participants (Oberhauser and Prysby, 2008; Conrad and Hilchey, 2011).

There were also benefits of using LEK to study CIBs. LEK has the potential to cover larger time scales than scientific studies. Most scientific studies of CIBs began after 1993 when concern arose over the declining population. Twelve of the 23 participants in this study had experience dating back at least twenty years indicating that a majority of the respondents had experience equal to or longer than scientific research on belugas in Cook Inlet. One of the greatest benefits of using LEK to address conservation issues is it allows stakeholders to be involved in the development and implementation of management strategies (Huntington, 1998). LEK and TEK are critical for co-management, a "continuum of arrangements involving various degrees of power and responsibility-sharing between the government and the local community" (Moller et al., 2004), which is granted by the Marine Mammal Protection Act and recognized by the UN (Mauro and Hardison, 2000). For co-management to succeed, communities need to feel that they are equal partners and that their knowledge is recognized and valued. Through such management schemes, conservation strategies may be more successful from the combination of scientific rigor and local and traditional experience and expertise.

The present study documented that CIBs react to a variety of disturbances including boats, aircraft, explosions, and other sources of anthropogenic noise. Most reactions were avoidance reactions – diving, leaving the area, changing surfacing behavior. In a few cases, belugas, young belugas, approached the noise source. A majority of reactions resulted in changes in behavior. Interruptions of behavior, even if short-term, have the potential to impact individual belugas if they are repeated (Tyack, 2009). In Cook Inlet, belugas have essentially abandoned foraging habitat in the Kenai River likely due to increased sport fishing activity though it is unclear whether this abandonment is due to noise or other aspects of human presence. Anthropogenic noise can also influence beluga communication. In other areas, belugas have changed the rate and frequency of their calls and even the call types used in response to approach by boats (Finley et al., 1990; Lesage et al., 1999). As reported in the present study, CIBs have reduced or ceased calling in the presence of airplane noise and construction noise (Table 3.4). Interference with acoustic communication can limit population growth which could interfere with the recovery of an endangered population (Tyack, 2009). Due to the potential serious effects of anthropogenic noise on the CIB population, this problem warrants further study. Future research on this issue utilizing LEK could seek to increase participation from certain user groups, particularly Alaska Natives. No participants in this study self-identified as an Alaska Native, and only two participants chose not to answer. Alaska Natives with knowledge of CIBs can be difficult to access, and researchers may find communities resistant to sharing their knowledge with outsiders (Huntington, 2000; Lewis et al., 2009) which can make obtaining their participation more challenging than obtaining participation from other user groups. Increasing participation in such studies in general may be a challenge moving forward given the controversial atmosphere surrounding the issues facing the

CIB population. Future studies should ascertain what activities or disturbances participants have observed and whether belugas were present in the area during these activities. This could allow researchers to discern whether participants do not report observations of beluga disturbance because they did not observe belugas in the area of potential disturbances or because belugas showed no reaction to the disturbance. Future research could also include a mapping activity to provide more information on where participants spend their time in Cook Inlet and where they observe belugas.

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Table 3.1 List of Questionnaire Questions

Demographic information
- What is your gender? (Male/Female)
- What is your age?
- Where are you from?
- Which categories describe you and your use of Cook Inlet?
  - Commercial fisherman in Cook Inlet
  - Sport fisherman in Cook Inlet
  - Subsistence fisherman in Cook Inlet
  - Non-fishing commercial user (i.e. Tug boat pilot, oil rig worker, tourism operator, etc.)
  - Researcher in Cook Inlet
  - Resource manager in Cook Inlet
  - Cook Inlet resident
  - Government employee
  - Member of Cook Inlet beluga recovery team
  - Other (please specify)
- How many years of on-the-water experience do you have?
- Have you seen Cook Inlet belugas? (Yes/No)

Alaska Native questions
- Are you an Alaska Native? (Yes/No)
  - Have you participated in a beluga hunt in Cook Inlet? (Yes/No)
    - How many years of Cook Inlet beluga hunting experience do you have?
    - What roles have you performed during these hunts?
    - Were any of these hunts successful?
  - Do you believe the Cook Inlet beluga population is sustainably harvestable? (Yes/No)
    - If no, why?
  - Do you believe beluga hunting will resume in your lifetime? (Yes/No)
    - If yes, will you participate?
  - Are you concerned about the loss of traditional knowledge of beluga hunting or beluga behavior? (Yes/No)
  - Do you currently receive beluga through a sharing network? (Yes/No)
    - From which communities?
    - Has the amount of beluga you receive changed since Cook Inlet belugas were listed as endangered? (Yes/No)
      - If yes, please describe
    - Has the listing of Cook Inlet belugas as an endangered population affected your life in other ways? Please describe

Cook Inlet beluga population
- In your time on the water, have you seen a change in the Cook Inlet beluga population? (No/Yes – the population has declined/Yes – the population has increased)
  - If you believe the population has declined, what do you think caused this decline?
  - Have you seen any signs of recovery in the population? (Yes/No)
    - If yes, please describe
  - What do you think are the main causes limiting recovery of the Cook Inlet beluga population?

Noise in Cook Inlet

Table 3.1 continued…

In your time on the water, has the noise level in Cook Inlet changed? (Yes/No)
If yes, how?
Do you believe noise affects Cook Inlet belugas (Yes/No)
If yes, how?
Have you observed Cook Inlet belugas react to natural sources of noise? (i.e. rain, falling rocks, cracking ice, etc.) (Yes/No)
If yes, please list the sound and how the belugas reacted
Have you seen Cook Inlet belugas react to manmade noise? (Yes/No)
If yes, please list the sound and how the belugas reacted
How do you think this reaction affected the belugas?
Do you think noise is a serious concern for the Cook Inlet beluga population? (Yes/No)
If yes, what do you think could be done to reduce the impact of manmade noise on belugas?

Table 3.2 Stakeholder Groups of Questionnaire Respondents

Self-reported membership in stakeholder groups by questionnaire respondents

Stakeholder Group	**Participants**
Commercial fisherman	9
Sport fisherman	7
Subsistence fisherman	1
Non-fishing commercial user	2
Researcher	13
Resource manager	4
Cook Inlet resident	12
Government employee	6
Cook Inlet beluga recovery team	5
Other	2

Table 3.3 Sources of Increased Noise Levels in Cook Inlet Identified by Survey Participants

Identified Noise Source	**Specific Examples**	**Times Reported**
Boat/vessel traffic	Small boats Large vessels "Unregulated boat traffic from the personal use fishery"	6
Oil and gas development/exploration	Seismic surveys	6
Coastal development		2
Port expansion	Pile driving	2
Air traffic		2
Increased fishing	Increase in charter operations Expansion of sport dip net fishery	2
Dredging		1

Table 3.4 Disturbance Reactions Reported by Survey Participants

Anthropogenic noise sources observed to elicit a beluga reaction are listed as well as the number of times the source was reported and the reaction of the belugas to the noise.

Noise Source	Number Times Reported	Reported Reactions
Boat	8	Leave area Avoid or move away Dive and not resurface Alter travel direction
Plane	7	Dive and not resurface or leave Surface less frequently Surface lower in water Cease phonating
Blast/explosion	3	Leave area Dive and not resurface Change surfacing behavior
Pile driving	2	Dive and quickly leave area Change swimming direction
Construction noise	1	Reduced calling Traveled along shore away from noise
Depth finder transducer	1	Approach boat
Anchor chain hitting deck	1	Quit surfacing Leave area Approach
Car	1	Dive and quickly leave area
Human voices	1	Dive and leave area

Table 3.5 Participants' Perception of Noise Impacts on Cook Inlet Beluga Whales

List of questionnaire respondents' answers when asked how noise affects Cook Inlet beluga whales, how the impact of noise on the Cook Inlet beluga population could be reduced, and what factors are limiting the recovery of the population

How noise affects Cook Inlet belugas	Measures to reduce the impact of noise on the Cook Inlet beluga population	Factors limiting recovery of the Cook Inlet beluga population
Masking	Manage for cumulative effects of noise Comprehensive records of anthropogenic noise in Cook Inlet Coordinate projects to prevent overlap of noise-producing activities	Prey abundance, availability, or quality Overwinter feeding success, particularly for juveniles
Temporary displacement		
Alteration of behavior		Stranding events
Injury or hearing damage	Make data from seismic surveys public to prevent redundancy	Predation on belugas
Stranding	Increase number of activities requiring permits	Unsustainable level of participation in personal use fishery
	Require cessation of noise-producing activities when belugas are nearby	Underwater noise
	Spatial or seasonal limitations on noise-producing activities	Cumulative effects of multiple stressors
	Further research Noise thresholds that affect belugas Playback studies Aerial surveys during seismic exploration	

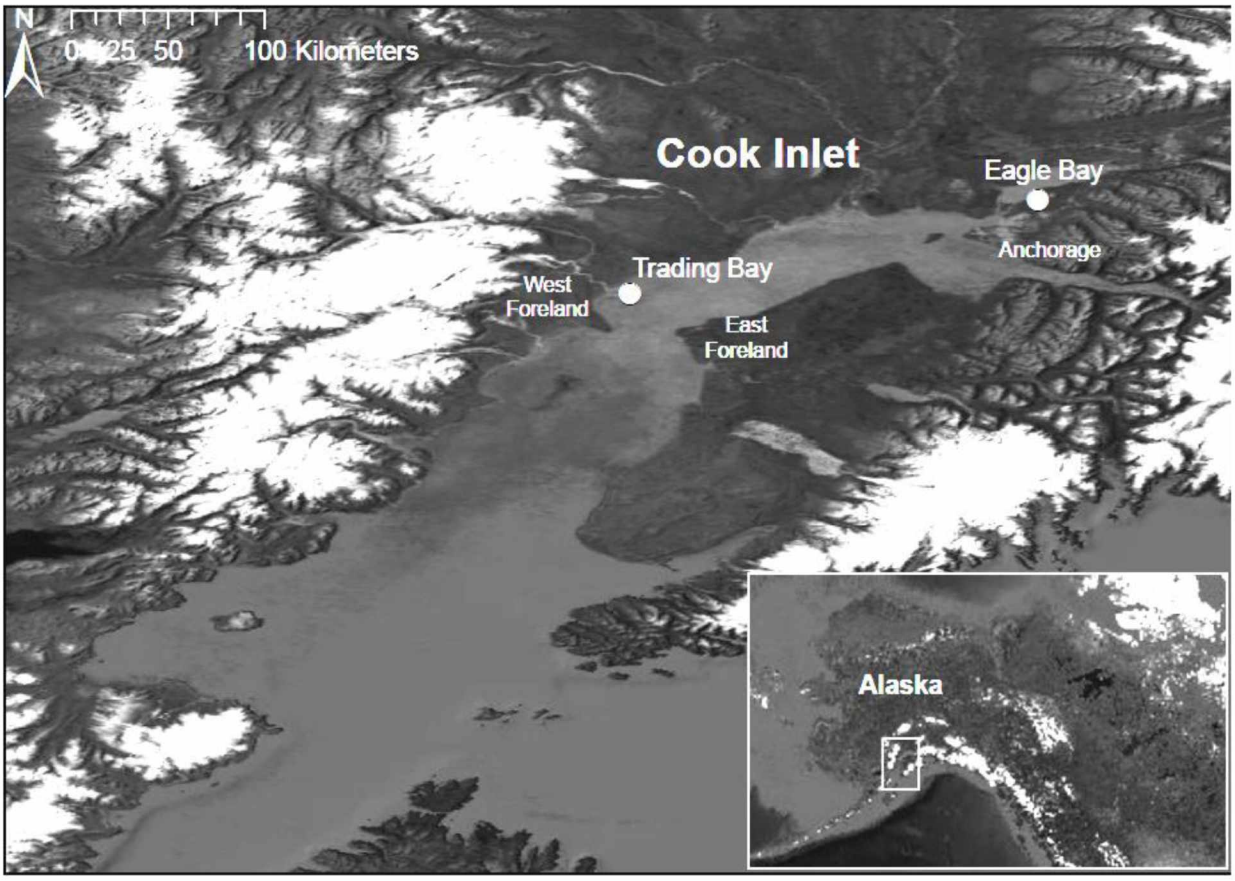

Figure 3.1 Map of Cook Inlet, Alaska. The location of Anchorage and East and West Forelands are indicated. Map extent indicated by the rectangle in inset map. (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.)

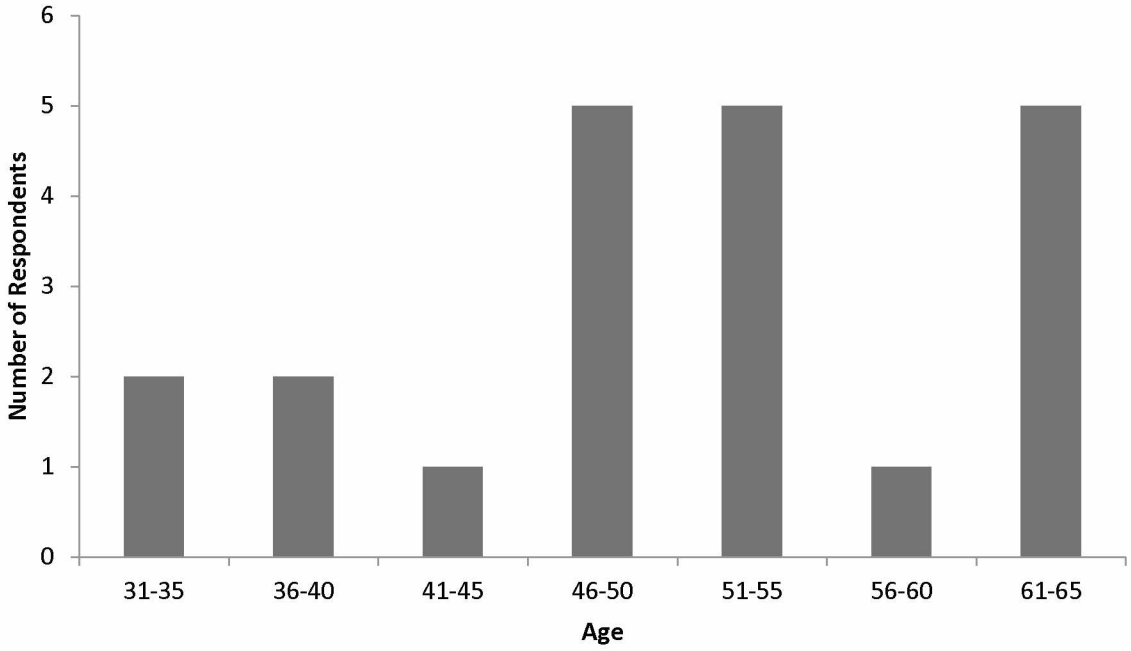

Figure 3.2 Histogram of Questionnaire Respondents' Age

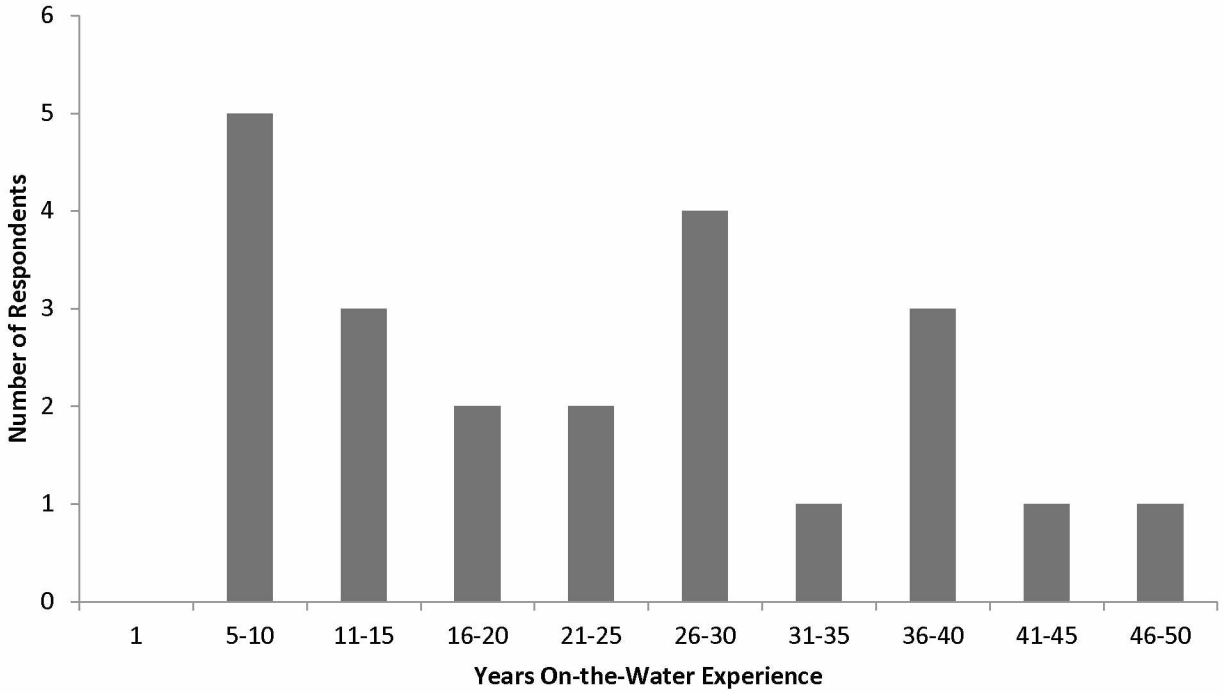

Figure 3.3 Histogram of Questionnaire Participants' Years of On-the-water Experience

Conclusions

Using interdisciplinary techniques, this dissertation research sought to improve our understanding of the potential impacts of underwater noise on the endangered Cook Inlet beluga population. In order to gain a greater understanding of how Cook Inlet belugas use sound, Chapter 1 utilized passive acoustics to study the acoustic behavior of Cook Inlet beluga whales and to determine if this behavior varied temporally or spatially within the inlet. In Chapter 2, passive acoustic data were used to characterize the ambient underwater noise environment in Cook Inlet and to determine if noise levels exhibited temporal or spatial variation. Chapter 3 was a local ecological knowledge study to document reactions of Cook Inlet belugas to noise disturbance. Together these studies provide greater understanding of how Cook Inlet belugas utilize sound and of the ambient noise environment in which they reside; these studies also provide insight into the potential impacts of noise on calling and other behaviors of the Cook Inlet beluga population.

The calling behavior of Cook Inlet belugas, reported in Chapter 1, varied seasonally and spatially. Within the study band width, whistles were the most commonly recorded call type for this population as is true for other beluga stocks (Sjare and Smith 1986b, Angiel 1997, Karlsen *et al.* 2002, Belikov and Bel'kovich 2007, Chmelnitsky and Ferguson 2012). This suggests that the predominance of whistle use is a trait of the species and is likely not attributable to unique behavior or unique habitat characteristics of the population. Pulsed calls made up a larger proportion of Cook Inlet beluga calls during the summer months compared to the winter months which could be indicative of higher levels of social interaction and foraging activities during this time of year (Gish 1979, Clark 1982, Brownlee 1983, Sjare and Smith 1986a) or could also be indicative of the presence of young calves during this time (Vergara and Barrett-Lennard 2008).

Click trains made up a larger proportion of the calls recorded in Eagle Bay than in Trading Bay possibly due to greater attention to navigation or foraging activity in Eagle Bay (Verfuss *et al.* 2009). Further study using a greater number of locations, spanning longer time periods, and sampling a greater frequency range would provide a more comprehensive understanding of Cook Inlet belugas' use of sound throughout the year and throughout the inlet. As marine mammal acoustic behavior is highly context-specific, varying with behavior, group composition, and other factors (Richardson *et al.* 1995), future studies linking visual observations with acoustic behavior would provide context for recorded calls and potentially allow the correlation of certain calls with certain behaviors or certain age classes or sexes.

Results in Chapter 2 indicated that sound levels in Trading Bay and Eagle Bay are highly variable. The loudest sound pressure levels (SPLs) were recorded in the 100 Hz third octave band reaching up to 109.56 dB re 1 μPa. Given the hearing abilities of the marine mammal and fish species present in Cook Inlet, sounds in this band are most likely to affect baleen whales and fish. Previous studies have shown that noise can cause fish to be displaced from an area (Slotte *et al.* 2004) and to release cortisol, a bioindicator of stress (Wysocki *et al.* 2006). Aside from fishery impacts, noise effects on fish could also have indirect effects on Cook Inlet belugas by affecting their prey. This was a concern raised by questionnaire respondents in Chapter 3. To further evaluate the potential for noise in Cook Inlet to affect fish, lower frequencies should be studied in greater detail. Mean SPLs were higher in the summer than the winter and higher in Trading Bay than in Eagle Bay. The differences in SPLs could be due to differences in human activity level. Human activity in Cook Inlet is higher during the summer than during the winter due to fisheries for anadromous fish runs in the summer and the presence of sea ice during the winter. Also more vessels transit past Trading Bay than Eagle Bay which is north of the Port of

Anchorage and Port Mackenzie, and there are several operating oil rigs which generate noise in the vicinity of the Trading Bay hydrophone. Monitoring of noise should continue in Cook Inlet to track changes in noise levels in the inlet over time and to determine if these changes are correlated with changes in the Cook Inlet beluga population. Future studies of noise in Cook Inlet should also include sound measurements in other areas that are more affected by human activity, such as near the Port of Anchorage.

The season of higher ambient noise levels in Cook Inlet coincided with the season of greater usage of pulsed calls by Cook Inlet belugas in these studies. Belugas have been shown to change the frequency or duration of their calls in response to noise (Lesage *et al.* 1999). It has also been proposed that belugas may change their call type usage in the face of ambient noise (Lesage *et al.* 1999). Pulsed calls are broadband, covering a wider range of frequencies, which may allow for greater detectability in the presence of noise compared to whistles which would be more easily masked due to their narrow band width. If pulsed calls are more easily detected by conspecifics in the presence of noise, the higher usage of pulsed calls in the summer may be an attempt to counteract the effects of masking. However, pulsed calls were more common in Eagle Bay which has lower ambient sound levels compared to Trading Bay. This suggests that the higher abundance of pulsed calls was more likely due to differences in whale density or behavior, including socialization level or communicative content. To more directly study the effects of ambient noise on the acoustic behavior of Cook Inlet beluga whales, a more controlled study, such as an acoustic playback experiment, would be needed. Future research should also span longer time periods in order to capture loud human activities, such as seismic surveys or dredging activities, which may be temporally limited.

The comparison of pre- and post-beluga encounter sound levels in Chapter 2 indicated that belugas were not driven out of Eagle Bay or Trading Bay by noise during the study period. The results suggested that belugas may be attracted to areas by sound. Their movements are more likely governed by tidal cycles (Huntington 2000) and potentially pursuit of prey (Huntington 2000, Hobbs *et al.* 2005). In Chapter 3, beluga attraction or approach was rarely reported by questionnaire participants. In almost every case it was young, gray whales that exhibited an attraction or curiosity. However, most noise sources reported to elicit a response in Chapter 3 were generally ambient noise sources. Other acoustic cues may serve as beluga attractants. Movement of sediment in these areas could increase sound levels. Disturbance of the bottom substrate could increase prey availability for belugas which consume some benthic prey including flounder, polychaetes, and crustaceans (NMFS 2015). One interviewee in chapter 3 reported that belugas seemed attracted to gravel being poured into the water and hypothesized the attraction may have been due to increased foraging opportunities as benthic prey species were disturbed. It is also possible that sounds produced by beluga prey species could increase ambient sound levels which could attract beluga whales to the area to forage.

In Chapter 3 survey respondents reported that Cook Inlet beluga whales react to a variety of anthropogenic disturbances including boats, aircraft, explosions, pile driving, construction noise, depth finders, and cars. More directed observations of belugas during noisy activities would provide more information on reactions of belugas to specific noise stimuli and could allow for observation of reactions at greater distances than is possible through local ecological knowledge studies. The reported responses of Cook Inlet belugas to noise were similar to those described in other areas (Richardson *et al.* 1995), generally exhibiting avoidance reactions to these stimuli by diving or vacating the area. Most reported reactions were short-term, however

study respondents reported a change in beluga presence in the Kenai River area over time and interpreted that to indicate that disturbance may have contributed to long-term effects on distribution of this population. To greater understand the potential effects of disturbance on Cook Inlet beluga whales, future research to attempt to quantify the effect of a disturbance reaction or the effect of remaining in the area of a disturbance would allow an estimation of the costs to individuals and the population. This could be done through a bioenergetic budget that could be used to evaluate the costs and benefits of various behavioral actions.

This dissertation encompasses research to gain a greater understanding of noise levels in Cook Inlet, how the endangered beluga population in Cook Inlet utilizes sound, and how this population reacts to noise disturbance. Underwater noise pollution may be a factor hindering the recovery of this population that has failed to rebound following conservation protection measures. Noise disturbance has the potential to affect belugas' behavior and may lead to long-term shifts in distribution of the population. Further research into the effects of noise on the acoustic behavior of Cook Inlet belugas would provide greater knowledge of how noise may affect their communication and navigation. In light of the low documented mortality due to killer whale predation, malnourishment, contaminants, and disease and the need for further research on changes in prey abundance, climate change, and the effects of underwater noise pollution, it would be valuable to consider the cumulative effects of these multiple stressors. While their potential impact may be small individually, when combined, these factors may have a synergistic and significant impact on individual whales and, in turn, on the Cook Inlet beluga population. Management of cumulative effects may be necessary to ensure the recovery of this endangered population.

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